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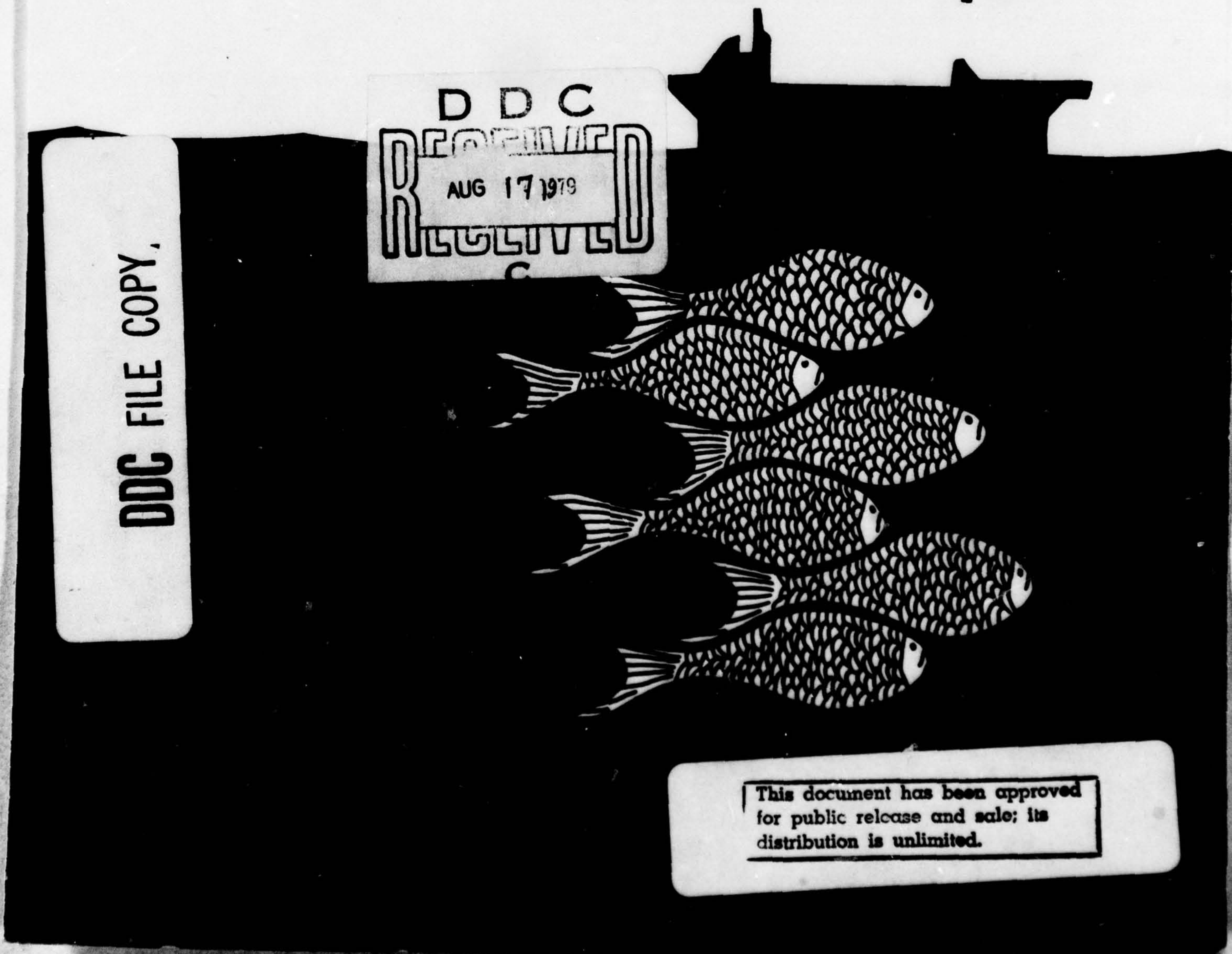
The Proceedings of the

Conference on Assessment of Ecological Impacts of Oil Spills



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The Proceedings of the Conference on Assessment of Ecological Impacts of Oil Spills

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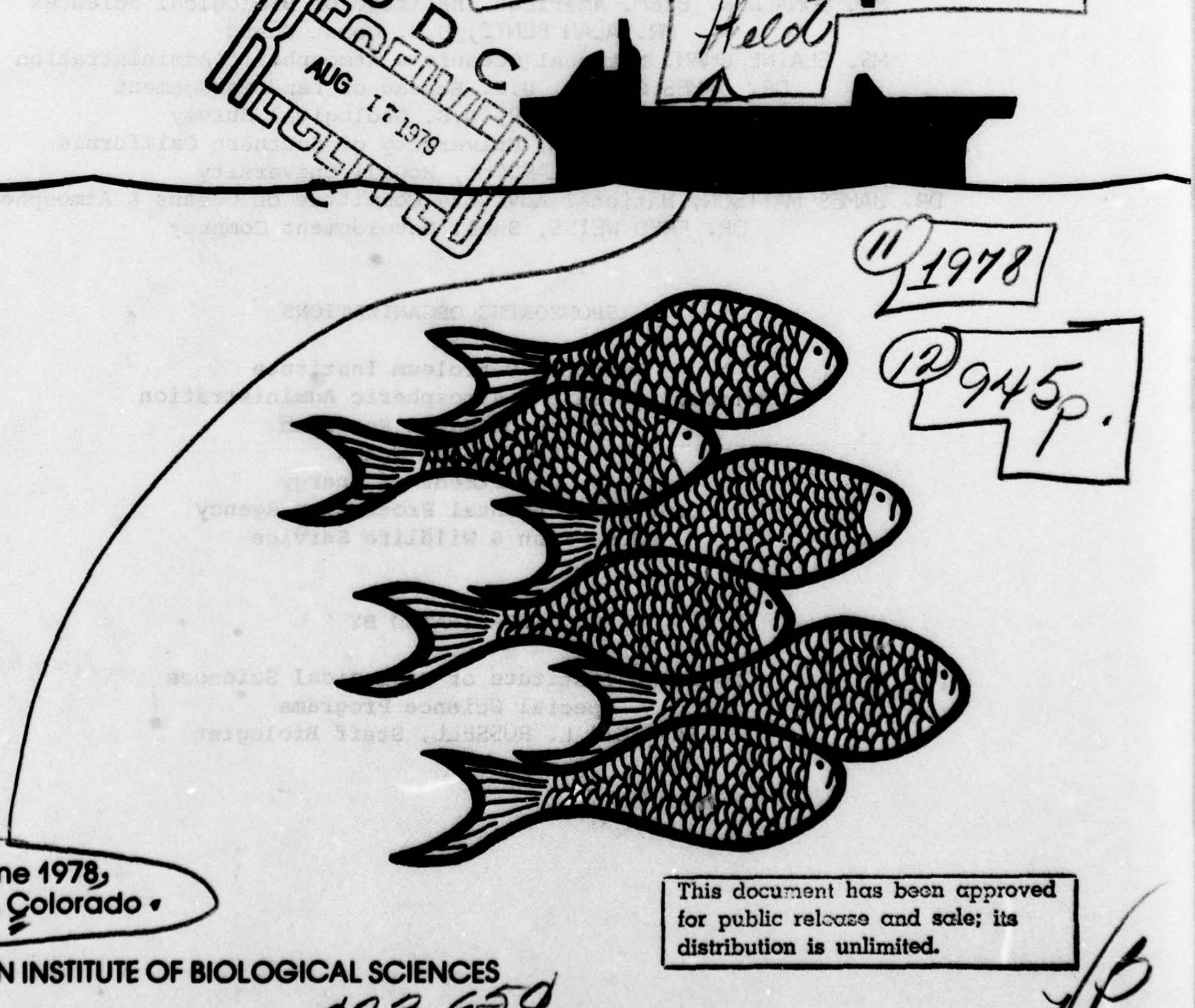

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14–17 June 1978,
Keystone, Colorado

AMERICAN INSTITUTE OF BIOLOGICAL SCIENCES

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CONFERENCE ON

ASSESSMENT OF ECOLOGICAL IMPACTS OF OIL SPILLS

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On behalf of the sponsors, I would like to thank all speakers presenting their research results; the foreign scientists and engineers who made the long trip to Keystone so that the Conference could benefit from their broad knowledge and experience; the Director and the staff--particularly Mr. Donald Beem, Head, Special Science Programs, Ms. Patricia Russell, Staff Biologist and Conference Coordinator, and Ms. Cynthia Moore, Staff Assistant--of the American Institute of Biological Sciences for convening the conference; the Keystone Conference Center management and staff for providing such an effective and hospitable meeting facility; the Conference's broad-gauged Technical Program Committee so ably chaired by Dr. Paul Lefcourt, U.S. Environmental Protection Agency; Mrs. Patricia Shenkle who served as the executive secretary of the Conference's Steering Committee; and, last but certainly not least, you, the participants and readers, for your enthusiastic support for this Conference.

Charles C. Bates

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OPENING REMARKS

Charles C. Bates
Science Advisor to the Commandant and
Chief Scientist, Office of Research and Development
U.S. Coast Guard

As General Chairman of this conference on "Assessment of the Ecological Impacts of Oil Spills", I am pleased to welcome you to a beautiful and efficient conference center for nearly four days of solid work mixed with a high degree of information transfer and mental stimulation.

It is now slightly more than a decade since the stranding of the tanker TORREY CANYON highlighted to the world the ecological, engineering, legal, economic, and governmental issues associated with the prevention, behavior, control and clean-up of oil spills. During this past decade, there have been dozens of books and reports, scores of meetings, and thousands of technical papers written on the general subject of the effect of petroleum hydrocarbons when released into the aquatic environment. Within the United States, presidents of both political parties--Nixon in 1970 and Carter in 1977--have seen fit to send special messages to the Congress regarding how the impact of oil spills on the biota and on our modern society might be sharply reduced. The Congress, too, has been extremely active on the legislative scene relative to oil spills, as have many state legislatures. Moreover, the media--particularly the television networks and the press--have kept the public sharply aware of the oil spill problem via the vivid coverage of such events as the stranding of the ARGO MERCHANT off Nantucket and the AMOCO CADIZ off Brittany wherein no human lives were lost, yet there was total loss of the cargo of petroleum into the sea.

With so much activity going on about oil spills, the question could be raised as to why a follow-up conference was needed after the one on "Sources, Effects, and Sinks of Hydrocarbons in the Aquatic Environment" convened by the American Institute of Biological Sciences in Washington, D.C., nearly two years ago. That conference explored and documented the 1976 state-of-the-art relative to the broader aspects of the fate and effects of spilled oil in water areas. However, it also became evident that a more definitive picture was needed regarding the scope of ecological impacts--both short- and long-term--that could be expected from oil spill incidents of differing types and magnitudes and in various geographic regions. Accordingly, some fifteen months ago, a formative meeting was held at the invitation of Dr. Jack Gould of the American Petroleum Institute and Mr. Ed Mertens of Chevron to determine whether a follow-up conference focusing on the assessment of the ecological

impact of oil spills was merited. The potential sponsors agreed that a conference documenting this topic was called for. Because of the subject's timeliness, seven sponsors were able to provide funds for optimizing participation by invited speakers. In addition, sponsors were pleased that the American Institute of Biological Sciences, a federation of more than fifty biological societies, was willing to convene the conference as it had done in 1976.

Meeting groundrules are the same as so well expressed by Dr. Sidney R. Galler, Deputy Assistant Secretary for Environmental Affairs of the U.S. Department of Commerce, in his introductory remarks to the previous AIBS conference of this type two years ago. He stated then:

> "This symposium is not intended to be positional in nature.....Rather this meeting (is) planned to provide a warm, congenial and secure intellectual environment to facilitate the exchange of knowledge and ideas free from the threats of harangue and purple prose."

You will find the conference to be comprehensive and fast-moving. Following three outstanding keynote speakers from the Federal Government, the petroleum industry, and a coastal state's Department of Environment, there are several papers by legal and economic experts on how the non-ecologist looks at the ecological impact issue. Next is a series of ten case histories of interesting oil spills, followed by sixteen research papers designed to update us on this fast-moving facet of field and laboratory science. Lastly, conclusions will be forthcoming from four mini-workshops to be held during the last half day of the conference wherein all participants can express their views regarding the present state-of-the-art in ecological assessment and point out what, perhaps, should happen next in both scientific and governmental circles. In this regard, the conference has drawn 290 registrants from 33 states and seven foreign countries, including Canada, Denmark, Italy, France, Norway, Sweden and the United Kingdom.

In addition to the formal portion of the Conference already mentioned, the last evening of the Conference features preliminary observations of the physical, biological, geological and shoreline cleanup aspects of the AMOCO CADIZ tanker spill off Brittany, France in mid-March, 1978. The speakers who will so kindly present this material on short notice are: Dr. Lucien Laubier, Director, Centre National Pour L'Exploitation des Oceans/Centre Oceanologique de'Bretagne; William P. Davis, U.S. Environmental Protection Agency; Jerry Galt, National Oceanic and Atmospheric Administration; Roy W. Hann, Texas A&M University; Miles O. Hayes, University of South Carolina; and James P. Marum, Standard Oil Company (Indiana). Because their observations are not yet finalized, they are not to be included in the formal proceedings.

OPENING REMARKS

Richard Trumbull
Executive Director
American Institute of Biological Sciences

It is a pleasure to welcome you to the second symposium on the topic of oil spills. As you are aware, during these days of our discussion there is activity in Washington to establish a super fund for compensating for losses incurred by such spills. It is inevitable that future arrangements for such compensation can derive only from an adequate assessment of losses, especially in the biological world.

Our review of case histories and evaluation of improvements in measurement will play a role in that future. Conferences and their reports tend to be identified with events and/or locales. It is appropriate that this conference is being held at Keystone because I will predict that it will serve as a keystone in future deliberations and its report will be identified as the "Keystone Conference report." The Program Committee has done an outstanding job of bringing the right ingredients together so let's put it all together.

KEYNOTE ADDRESS

Rear Admiral Anthony Fugaro

Chief, Office of Marine Environment & Systems
U.S. Coast Guard Headquarters

GOOD MORNING, ladies and gentlemen. It is indeed a pleasure to appear before you as a keynote speaker.

Over the past two decades, there has been an ever-increasing interest in the preservation of our environment. Of particular interest to much of the public, as well as several government entities, is the protection and preservation of marine and water-related resources. Widely publicized marine casualties such as the TORREY CANYON, the METULA, the SANSINENA, and the ARGO MERCHANT have contributed significantly to the heightened awareness and concern about spills of oil on our nation's waters. The recent AMOCO CADIZ disaster has sharpened this focus and will probably become a benchmark against which future anti-pollution efforts will be evaluated.

Following the TORREY CANYON spill, it became apparent that, while it was important to develop equipment and methodologies to respond to and cleanup oil spills, there must also exist a vigorous program dedicated to the prevention of these spills. To that end, the 1972 Amendments to the Federal Water Pollution Control Act (FWPCA) established, as national goals, safe water by 1983 and clean water by 1985. The prevention programs spawned by the FWPCA along with innumerable research projects, have given us a very good start on achieving the goals set by legislation.

My intent this morning, is to put the oil spill situation into perspective by using a bit of history to show where we have been; a look around us to show where we are; and a glimpse into the crystal ball to predict where we are going.

The Coast Guard had had limited authority in the maritime pollution field prior to passage of the Water Quality Improvement Act (WQIA). That authority was generally limited to the enforcement of rather vague laws, the Refuse Act of 1899, for example. By authority of the WQIA, the President, through Executive Order 11548 named the Coast Guard as the agency responsible for receiving reports of, and investigating, oil spills on the waters of the United States. The WQIA was substantially superceded by the 1972 amendments to the Federal Water Pollution Control Act (FWPCA), and Executive Order 11735 greatly expanded the Coast Guard's responsibilities and authority. Following marine pollution incidents in 1976 and early 1977 (the ARGO MERCHANT and the HAWAIIAN PATRIOT) a major piece of legislation passed - the 1977 amendments to the FWPCA, otherwise known as the Clean Water Act.

That is where we have been. We have discovered that since 1973, there have been an average of about 11,000 oil spills per year in U.S. waters, spilling an average of 19 million gallons per year. Further analysis has shown that, while the location of these spills, whether on any of our coastlines or the inland region, has not been a significant indicator of problem areas, the relationship between the frequency and volume of the spills is, however, quite important. While newsworthy, the massive spills from vessels like the ARGO MERCHANT are not nearly so environmentally harmful as the tremendous number of minor to medium size spills. The large, or major, spills generally effect a relatively small geographical area when compared to the dispersion of the minor and medium sized spills. For those of you who desire to look at this general area in more detail, I have prepared a technical paper which will be published in the proceedings of this conference.

This brings us to where we are today. Technology for the response to, and cleanup of, oil spills has developed at a remarkable rate. But for a few specialized problems, such as high seas or open water removal of oil, removal in a fast current, or in an extremely cold weather environment, we are in pretty good shape when it comes to cleanup or mitigation of pollution from oil. These special areas of interest are under consideration in several Federal and private research and development efforts. In response to direction from President Carter, we are evaluating the cost and feasibility of upgrading our capability to respond, within six hours after notification, to all spills of up to 100,000 tons of oil.

But response - or even improved response capability - is not the answer. Prevention is the key, if we are to make any progress towards our national goals of safe water by 1983 and clean water by 1985. The Tanker Safety and Pollution Prevention Conference held in February of this year in London, in response to U.S. initiatives, along with the Conference on Training and Certification of Seafarers due to start next week in London, are two major milestones in effecting prevention measures.

In the April 20th edition of the Federal Register, the Coast Guard published a schedule for the implementation of the international standards for vessels adopted at the February London Conference. For vessels and oil transfer facilities, the development of amendments, or additions to comprehensive pollution prevention regulations is well underway.

Recent developments in surveillance equipment and techniques are also being put into practical use. But once again, the question arises: How well are we doing our job of preventing oil spills? Let's look again at the data. If one were to simply view the oil pollution problem as being one of frequency and volume of oil spills, the impression received is frustrating. Millions of dollars, and tens of thousands of man hours have been expended in an effort to curb oil

I think you can agree that, as damaging as they were, the massive oil spills of the past are proving to be true friends of the marine environment. For without their occurrence, the important pieces of legislation I mentioned this morning, plus the recent accomplishments nationally and internationally, may never have come to pass.

But, the reporting of spills alone does not tell us everything we want to know. A more important question arises: How do we know whether or not our efforts, and the efforts of the various Federal, state, and local agencies has provided any positive results? A means of collecting, storing, and analyzing the data produced from the various investigations and responses to water pollution incidents had to be developed. And so it was, that the Pollution Incident Reporting System, or PIRS, was developed and implemented by the Coast Guard.

Initially, PIRS was conceived as being a management tool for the Coast Guard's Marine Environmental Protection program manager. But, as it turns out, PIRS has become much more than a simple in-house information system. As the program developed in the early seventies, we found that the number of users of the information contained in PIRS, as well as the diversity of disciplines of those users, far over-shadowed its limited role within the Coast Guard. Today, the users include the Congress, Federal agencies, industry, academia, special interest groups, and private citizens. We estimate that the Coast Guard now receives reports of over 80% of all oil spills on United States waters. For this reason, the data base established in PIRS has become the most comprehensive system of its type in the world.

I have told you who the users are, but I have not told you to what use this massive collection of data may be put. Simply stated, the data provides a means for measuring the effectiveness of the Marine Environmental Protection program, and it provides a foundation for further study and analysis of the marine pollution problem.

In our analysis of the data available in PIRS, we seek to observe trends. The trends of location, frequency, volume, spill distribution, materials spilled, the time of the spills, the sources of the pollutant, and, most importantly, the causes of the spill incidents. In short, the PIRS data base supplies the kind of information necessary to provide a general picture of the United States' oil spillage situation.

In September of 1977, we combined the data contained in PIRS with the data in our Port Safety Reporting System. This amalgamation produced the Coast Guard Marine Safety Information System with computer terminals installed in each of our Captain of the Port offices throughout the nation. Our field people now have the ability to get a full picture of the safety inspection and pollution incident record of every tanker, whether it be foreign or United States. With the assistance of the Marine Safety Information System, we are now in a better position to keep sub-standard vessels from entering our ports.

Since 1970, the United States has increased its importation of petroleum at an average annual rate of 13.4%. That means that we are bringing in 132% more petroleum today than we were in 1970. The importation of crude oil alone, during the same period, has increased at an alarming 339%. This importation increase directly reflects the increase in the transportation of petroleum products with an attendant increase in the potential for oil pollution.

Oil carrying vessels, i.e., tankers and tankbarges account for about one third of the number of oil polluton incidents and about two thirds of the total volume of oil spilled. One additional factor that might not be so apparent is that in 1970, we were probably aware of less than 50% of the oil spill incidents in the United States. As previously stated, with the advent of the FWPCA Amendments and their penalties for failure to report an incident, we now estimate that over 80% of oil spills in U.S. waters are, in fact, reported and investigated. Taking both factors into account, i.e., increased shipment of oil and more accurate reporting of oil spills, and comparing them to a stable spill incidence trend shows that we are making tremendous strides towards national goal achievement.

Now, what about the future? Some have argued that with rapidly diminishing oil reserves, we will most likely see an end to <u>oil</u>, before we see an end to pollution <u>from</u> oil. I view that opinion as overly pessimistic. On the other hand, the national goal of clean water by 1985 may be overly optimistic. I think that the only reasonable, and practical view is one recognizing that as long as we have oil, and as long as man is involved in its transportation, accidents will happen and <u>some</u> pollution will result.

We must, however, strive to absolutely minimize any level of pollution. In the next few days we will be assessing the ecological impacts of oil spills. I have no doubt that the assessment will clearly support the need for increased efforts on the part of all of us. And, while I say that we have made progress in the face of a tremendous increase in the amount of oil being shipped, I also say we need to do more - much more! Improved design and construction features for new vessels; modification of existing tankers to achieve cleaner ballast water; improved management and regulation of the navigation of vessels; and finally, improved crew standards are areas where Coast Guard preventative efforts will, hopefully, make further progress in eliminating oil spills in the years to come.

Once again, I want to thank you for the opportunity to speak to you today.

KEYNOTE ADDRESS

L. P. Haxby

Manager, Environmental Affairs
Shell Oil Company

ENERGY AND OIL - A BALANCE

When I began my career in the petroleum business, energy was cheap and abundant.

Now, oil and natural gas are neither cheap nor abundantly available.

Three-fourths of our energy supply today comes from crude oil and natural gas. Each man, woman and child in the U. S. Consumes petroleum products at a rate of three gallons a day, 365 days a year.

Our total demand for energy has doubled in the past 20 years.

Our transportation industry is completely dependent upon crude oil. Forty percent of all the oil we use is devoted to fuels for automobiles, airplanes, trucks, and trains.

Our farmers produce more food than any other nation, and their harvests depend upon petroleum.

And the products that are made from petroleum include much more than gasoline and motor oil. There are more than 200 common, everyday consumer products that are made from petroleum. Including fuel, fertilizer and pesticides for the farmer.

Our economy literally runs on petroleum.

And despite the complaints we all make about the high price of energy, it is a bargain. For example, the gasoline bill is a smaller part of the American wage earner's expenses than it was 20 years ago. In 1955, a manufacturing worker had to work 2.3 hours to pay for a 15-gallon tank of regular gasoline. Today, he works 1.8 hours to pay for the same amount, a decrease of more than 20 percent.

One of the reasons for this is the efficiency of, and the competition in, the energy industry.

Huge capital investments and other resources are needed by these companies. Consequently, there is a great incentive to use these large sums of money as efficiently and productively as possible. This incentive has resulted in the growth of a number of large companies. And this bigness is not bad, for it has benefitted consumers greatly in keeping prices down.

You are familiar with terms like "energy crisis" and "fuel shortage." These terms are becoming trite and almost meaningless, but they translate into a reality that must be faced, and the sooner the better.

The American Petroleum Institute reported in January that the U. S. is now importing just under half of its crude oil supply. Eight years ago, we imported only 25 percent.

Yes, it is a crisis if our crude oil supply can be interrupted at any time. Even our military strength can be threatened. It is also a crisis if our economy faces steady erosion of its strength, an erosion partially due to our steadily increasing payments to foreign producing nations for imported oil.

Why? Because the Organization of Petroleum Exporting Countries holds the key to a large share of our energy supply, and its members will determine the price and availability of our imports for at least the next ten to fifteen years.

The problem, therefore, is that we have to face and surmount a long-term shortage of petroleum and maintain a continuous supply during the interim.

But we are not without a solution to our energy problem. We can realize energy savings with conservation. We have large areas of the Outer Continental Shelf of the U. S. which are still relatively unexplored for petroleum resources. We have large reserves of coal. We are working on solar energy technology, and striving to make use of nuclear power. And we may even be able to tap the potential of oil shale.

The challenge today is to recognize the reality of the problem and to act quickly and constructively to solve it at reasonable cost.

Our domestic production has not been able to keep pace with energy demand, and the situation is expected to continue to deteriorate until the government and the public fully realize that we must test the potential of all of our domestic unexplored areas. These areas include the Atlantic offshore, the Pacific offshore and the offshore provinces of Alaska.

How much undiscovered domestic oil there may be there is unknown. There may be relatively little, and there may be giant fields like the Prudhoe Bay discovery of Alaska's North Slope.

Because we are so heavily dependent upon petroleum, the process of switching to alternative fuels such as coal and nuclear power is going to be slow. We should not expect to see a solution to the energy problem until some time at the end of this century.

The challenge is awesome. Not only must new technologies for producing energy be developed and proven, but there also must be parallel developments and improvements in the technology to protect the environment. These two goals are inseparable, for our country is committed to both energy production and environmental protection. The two are not necessarily opposing goals, but they often cause conflicts.

Some groups want virtually no risk to the environment. We could achieve it by having no development at all. But we can develop our energy resources with limited impact on the environment. A reasonable compromise between development and environmental protection is attainable, and it absolutely must be achieved if inordinate delays in development programs -- delays so prevalent today -- are to be alleviated.

Oil spills, large and small, have long been of concern. Unfortunately, mechanical and human failures, and the hostility of the environment cannot be completely removed as causes of occasional oil spills. But prevention measures, both in training and mechanical design have and can further reduce spills.

Progress has been made on containment and recovery methods of oil on water. In addition to continuing research efforts on containment and recovery of oil at sea, some other areas of research to improve control are:

- Methods of off-loading tankers at sea in an emergency situation.
- Methods of identifying oils, both in producing areas and in transportation, for proper identification of pollution sources.
- Definition and classification of oil-spill treating agents for both offshore and onshore, to provide guidance and safeguards in their use.
- Advanced techniques for rapid and efficient beach and shoreline cleanup, restoration of these areas, and methods of disposal of clean-up oil.
- Development of improved material specifications, testing procedures, and instrumentation.
- An early and continuing program on fate and effects of oil in the marine environment.

And this takes us to today. We are here to compare information on these latter studies: the fate and behavior of oil in water and its effect on the marine environment.

There is a growing interest that local pollution incidents may affect the ecological balances of the marine environment. Investigations of this possibility are proceeding, and the global problem of oil on public waters is a matter of immediate concern to the U. S. petroleum industry.

We are living in a time when we are placing increasing emphasis on the conservation of the natural environment in which we live. At the same time, we must continue to grow economically in order to achieve all of our Nation's needs, including the adequacy of the environment.

Therefore, in the current process of harmonizing values, we all must recognize the interrelationships between the basic need for conservation of our environment, and the requirement for energy and the inevitable cost to be paid.

There is little doubt that much of our response to the present energy crisis is being formulated by a relatively few people who call themselves "environmentalists." This is not to say that we do not face enormous and critical environmental problems and that there are not enormous numbers of people who are dedicated to trying to solve them. The quarrel is with those who say there are no reasonable alternatives, but propose solutions which entail delaying or abandoning present, feasible, and proven technology, and "waiting for" solutions that are negative, impractical, and "just on the horizon."

Whether well-meaning or unenlightened, it is these nameless people who are leading us into a "no-growth" movement until, and if, the Utopian ideals come into being. Stopping growth can only mean falling behind, with all its economic consequences. It is only through the accumulation of social wealth from previously successful technologies that makes it possible to introduce new technologies.

I think the greatest misconception about "stopping growth" is the assumption that things will stay pretty much as they are. They will not. When growth stops, regression begins.

Just recently, the administration drafted a bill to reduce the delays in licensing and building nuclear power plants -- this has been in the works for 12 years. Party as a result of the legal wranglings, the number of nuclear units ordered by electric utilities in the U. S. dropped to four last year from the record number of 41 in 1973.

Since each new nuclear plant makes the Nation a bit less dependent on costly and unreliable foreign oil, the die-hard opponents have succeeded in slowing the country's progress toward greater security of energy sources and aggravated the Nation's trade deficit.

Environmentalism has presented itself to us as a form of "science," but it only borrows the language of science to serve its purposes. It is not scientific, either in its origins or its methods. It could easily turn anti-scientific, and already has in many instances.

In 1973, a letter to the New York Times stated that "the Atomic Energy Commission has reported that the Storm King hydroelectric power project by then already delayed 11 years might destroy 75 percent of the annual hatch of striped bass in the Hudson River." Senator Edward Kennedy asked the FPC for a "brief and worthwhile delay" because of the impending "destruction of 75 percent of the striped bass" off the coast of Cape Cod. Senator Abraham Ribicoff sponsored an "information meeting" on the report, and a Congressional hearing was eventually arranged. The testimony was inconclusive, but the environmentalists simply declared themselves the winner and carried the "new evidence" back to the Court of Appeals. The court ordered the FPC once again to reopen the hearings for a new study on fish life in the Hudson.

The "brief and worthwhile" delay has cost Consolidated Edison $20 million -- one-sixth of the original cost of the plant. The money was spent for a third major fish study which took four years to complete, involved seven major universities and scientific institutions, and came to essentially the same conclusion reached by Con. Ed.'s lone scientists more than ten years before -- that about four to five percent of the eggs and larvae would be entrained by the plant, and that the total fish population would not be affected.

Two observations show that there may be something to the utility's side of the story. The three Indian Point plants now take in more water than the Storm King plant would, yet after nearly three years of operation, AEC scientists admit that there is no evidence that any portion of the river's fish population has been affected. (The amount of fish scraped off the screening devices each day would fill an average bucket.) And even now 16 years after inception the two million killowat pumped storage Storm King project has never been built despite the fact that the project was never denied -- it was just delayed to death.

This extreme on one side has brought an extreme from the other side.

There's a group of lawyers in Sacramento, California, who say they represent the other American -- the taxpayers who like freeways, business growth, jobs, and who feel they are being overwhelmed by special interest groups.

The group's name, the Pacific Legal Foundation, is directed by Ronald Zumbrun, who says he got tired of the general public being under-represented while special interest groups had seemingly limitless legal aid. In less than five years, Zumbrun points to successes in getting the Concorde SST to land at Washington, D. C., fighting racial

quota systems in the construction industry, halting enforcement of the 160-acre limitation in federally irrigated agriculture, and gaining the right to use DDT to fight tussock moths that were devastating Pacific Northwest timber.

This isn't likely to stir cheers from liberals or conservationists, but that isn't the point. Zumbrun says that there hasn't been a balance of justice between liberal and conservative interests in a number of social, environmental and economic disputes that end up in court.

And there's a bigger point to be made here. That we are in an adversary position. Let's take a look at that for a moment. Do we take pride that we are one people -- Americans, if you will -- fighting for the common good? We are divided. We have divided ourselves into different groups: blacks and whites, rich and poor, young and old, business and labor, gays and straights, liberals and conservatives.

Dr. Elspeth Rostow, Dean of the Lyndon B. Johnson School of Public Affairs at the University of Texas, recently called on business and government to end their adversary relationship.

Speaking at the close of the 3rd International Petroleum Conference, Dr. Rostow said the adversary position of government and business "does this country no good." There is a need for a partnership between business and government, because the country is moving into a time of crucial national change.

So this is the challenge that I ask this conference to undertake. A balance between business and government, between energy and environment, between energy need and consumer cost. Consider the damage done in the various oil spill incidents, learn how we can better protect our waters, bays and estuaries, but use some common sense in applying this knowledge for the benefit of everyone.

I would like to leave you with this image from here in the west: Our wagons are all in a circle. We are conserving our supplies but they are running short. When we send eager riders out over the next hill for help, their horses kick up dust and pollute the air. Worse yet, when they return with the goods they make a little profit for their labors.

I am not suggesting guarantees that there are no more rocks in the road ahead, no more hills to climb, nor that it can be done without kicking up some dust. All I ask is that we quit pouring sand in our own wheel hubs, quit shooting holes in our own water barrels, and get on with our jobs -- all of us -- from the producers of energy to the solvers of environmental problems. We can work together in a common sense sort of way.

KEYNOTE ADDRESS

Evelyn F. Murphy

Secretary of Environmental Affairs
Commonwealth of Massachusetts

OIL SPILLS: THE DIVERGENCE OF PUBLIC VIEWS

THE SCHISM

I have been asked to represent the public views on oil spills. But there are many public voices now days -- federal agencies, state governments, municipal governments, public interest groups, and on and on. Unfortunately, we are not speaking with one public voice.

So, I want to talk to you today about why we are not together by describing a most disturbing problem -- the difficulty of trying to work with the federal government to develop public policy. To illustrate this problem, I want to characterize for you the alarming schism that has developed between Massachusetts and the federal government in our efforts to develop public policy on the use and management of our ocean resources.

I do this for two reasons. First, I believe that Massachusetts is not alone in its frustrations these days with federal agencies, other states and public interest groups are equally frustrated; and second, because our difficulties and differences point to some fundamental rearrangements that I think must occur between the federal government and the states, if we ever are going to develop a means of creating public policy -- in whatever area -- that reflects the diverse needs of this nation.

I urge you to hear my remarks not as an attack on any particular federal agency, but, hear the principles of the differences. That is what I want to get across to you this morning.

Let me start, then, by describing the nature of the schism that has developed over ocean policy between Massachusetts and the federal government, because I think it illustrates the complexity of the basic problem.

To begin with, we all agree --scientists, technicians, academics, state officials, federal officials --all of us--that we must manage our oceans to provide for a multiplicity of needs. We need to provide energy and energy fuels, food, minerals, transport of cargo, and so on. We also all agree, all of us, that the public has a vested interest in good management of the oceans. Man's survival depends on such management -- of that there is no doubt.

So there are basic, fundamental points of agreement. But, then there are the differences. These differences, upon analysis, are two-fold.

First, we in Massachusetts have been shocked to find ourselves differing with the federal government on the quality of ocean management we expect; the quality that, in our judgement, is critical to accommodating the many demands for the same area of ocean. Put bluntly, our standards are higher than those of federal agencies.

We started in a spirit of collaboration with federal agencies in the aftermath of the ARGO MERCHANT to reform and improve many aspects of ocean policy. Yet, given the experience of the last several years, we have lost our enthusiasm and our innocent beliefs. In short, we have become disenchanted.

We now recognize that our differences have not been recognized for what they really are: namely, in dimensions of policy that are just as important as those on which we all agree. Unhappily, collaboration has turned into confrontation.

Let me explain with three examples. Two examples flow directly from our hope and expectation that the experience of the ARGO MERCHANT, with its threat of disaster that thankfully did not materialize, would awake both the states and the federal government to an urgent need for change in both policies and procedures. The third example is the story of our state's insistence that oil exploration on the outer continental shelf be conducted only with appropriate safeguards to both environmental and human needs. In all three examples, we in Massachusetts eventually were forced to move from collaboration to confrontation in our dealings with the federal government.

EXAMPLES

THE NATIONAL CONTINGENCY PLAN

First, there were our attempts to make reforms in the national contingency plan for cleaning up oil spills.

The ARGO MERCHANT taught us many things about the way states were to be treated by federal agencies handling a major oil spill off our shores. For example, it took the Coast Guard four days to notify the Governor of Massachusetts of the conditions facing the state. To compound the insult, we only got this information because the Governor intercepted the ranking admiral at the Boston Airport as he was travelling in and out of Massachusetts for a flight over the wreck.

Then, when the ship broke up, we found ourselves searching the country for boom equipment. No real contingency planning had been done beforehand to determine when and where to get equipment. No decisions had been made as to which parts of the coastline clearly needed protection before other parts. There was no budget for picking up oiled birds, or for damage assessment, nor were agency budgets available for advancing costs of clean-up. There was no provision for a strike force nearby: instead, a crew of courageous men had flown from North Carolina to face one spill just after they had finished handling another.

We learned the hard way that the National Contingency Plan at that time consisted of a great deal of paper reassurance of federal responsiveness but

little practical evidence to support it. The Plan included the involvement of ten federal agencies, having what amounted to ad-hoc, varied and part time commitments to oil spill responses. There was literally no defined role for the state in this process. It was as if it had been determined that a state had little interest in or little contribution to make toward responding to a potentially catastrophic oil spill in its coastal waters.

We made the obvious conclusion: the National Contingency Plan needed to be rethought and redone. So we went to work. Massachusetts officials testified before congressional committees. We presented our analyses to the Coast Guard. We wrote memoranda, attended innumerable meetings and made uncounted telephone calls.

One year later, the Coast Guard responded. It issued a revised regional contingency plan for the North Atlantic which, in essence, was no more than a more elaborate telephone directory of people to call in the event of a spill. No results of "war gaming" were presented, no federal analysis was offered of critical ecological areas that could realistically be protected. After one year we could point to no substantial improvements in the Contingency Plan... and we were facing another winter.

Finally, in April of this year, after many discussions with the members of the National Response Team and the Council on Environmental Quality, Massachusetts formally filed a rulemaking petition with CEQ on the National Contingency Plan. The petition establishes clear lines of authority for response, makes affected states partners in the response, and requires the kind of planning and quality of response that we had been seeking.

But, and I cannot emphasize this point enough, it took a legal action in the form of a rulemaking petition to get the kind of review and response from federal agencies that we had tried cooperatively and collaboratively to do for one entire year without noticeable results.

TANKERS STANDARDS

The other example that arose from the ARGO MERCHANT spill has to do with the need for reform of tanker standards.

The story is almost the same. In the aftermath of the ARGO MERCHANT the President of the United States issued a directive to raise vessel standards. Massachusetts worked with the Council on Environmental Quality, the Office of Management and Budget, and with many other federal agencies, helping to formulate the standards that seemed, obviously and to all, to be necessary.

Five months later, the Coast Guard submitted a proposal rulemaking for oil tanker vessels. The rulemaking called for urgently needed mandatory structural and navigational requirements for tankers in United States waters. The proposal signalled a potentially significant decline in spills resulting from groundings or structural failures -- the largest single cause of oil spills.

That proposal was never adopted. Instead, the Coast Guard decided to await the outcome of the February 1978 International Maritime Consultative Organization's meeting. Again, a full year elapsed with no improvements in

federal standards having been implemented. In this instance, the international meeting produced yet another set of standards. Some of these were more stringent than the Coast Guard's, but many were less clear. Most important, all lacked the power of enforcement until either ratified through a process that would take at least five years, or more likely, until eventually promulgated by the Coast Guard.

Again, one and one-half years later with no changes even in sight, Massachusetts resorted to its only recourse: a formal rulemaking petition that has recently been filed with the Secretary of Transportation. This petition calls for stringent and relatively immediate structural and navigational requirements for tankers and barges carrying oil through United States waters.

OUTER CONTINENTAL SHELF

Now let me illustrate my point with one final example -- the state and federal approaches to the exploration and development of oil and natural gas on the outer continental shelf.

Here the confrontation between Massachusetts and the federal government entered the courtroom, with Massachusetts sueing the Interior Department this past January to postpone the lease sale on the Georges Bank until adequate environmental safeguards were instituted.

This situation puzzled and surprised many, for Massachusetts had been working with the Interior Department staff and Secretary Andrus on almost a daily basis since the Carter Administration took office. In fact, far from opposing off-shore oil exploration, Massachusetts recognized that it was necessary. Governor Dukakis and I had met with Secretary Andrus prior to his confirmation hearings in January 1977 to tell him of our desire to see off-shore oil exploration begin, as long as adequate environmental safeguards were there, too.

You must understand: for us the Georges Bank is unique. Fifteen percent of the world's fish food comes from this area. And for Massachusetts, 85 % of the catch of the state's fishing industry is derived from this area of the North Atlantic. This fishing industry, along with tourism, contributes over one and a half billion dollars to the state's economy annually. So, for Massachusetts, our real need for additional oil and gas reserves is combined with our need for adequate environmental safeguards to ensure compatibility of oil and fish, and to protect our beaches from oil slicks. For us, our stand was an important economic issue, not esoteric environmental extremism or mindless no-growthism.

We were clear with Interior about the safeguards we wanted, and documented our concerns in written communications. Moreover, these required safeguards remained the same over time: a second impact statement before development; a compensation fund for fishermen whose gear is damaged by oil operations; an oil spill liability provision that will provide for immediate clean-up and also restitution to affected coastal property and businesses; a provision for

the Secretary of Interior to suspend a lease whose continued activity could cause substantial environmental damage; and environmental baseline studies before development got underway.

We did not care whether these safeguards were accomplished administratively or through the passage of Congressional OCS Lands Act Amendments. We only wanted these safeguards in place at the time of the Georges Bank lease sale. But they were not.

Once again, Massachusetts, after long months of negotiations and good faith attempts at collaboration, was forced into a position of confrontation.

Interior told us that the safeguards we insisted upon were also desired by the federal government, but Interior was determined to hold to their announced date for the lease sale. In a last desperate move, Massachusetts aligned governors from a half dozen other states to join with us in a request to Interior for delay until the OCS Lands Act Amendments were passed by Congress. That request was denied.

So, Massachusetts filed a motion in federal district court for a preliminary injunction to stay the sale of leases on the Georges Bank until adequate safeguards could be put in effect. The court granted the motion and the First Circuit Court of Appeals upheld the ruling.

One has only to read the opinions of the District Court and the Court of Appeals to feel some sense of reassurance that we are not alone: that the federal courts recognize, long before the federal bureaucracy does, the significance of high quality management of our oceans. As Judge Campbell wrote: "There may be issues more important than ones involving the future of the oceans of our planet and the life within them, but surely they are few."

These examples lead directly into the issue we are facing here today -- the problems of damage assessment.

DAMAGE ASSESSMENT

The potential for yet another serious confrontation between federal and state agencies is here again. The damage assessment program now being developed already shows signs of becoming administratively splintered, and therefore, environmentally ineffective. The time and means to confront this issue should not be through after-the-fact petitions or testimony at some future congressional hearing. Our differences on the quality of plan and the timing of its implementation must be addressed now.

For it is essential that the program be under charge of a single agency. And it is essential that the assessment program be simplified. We cannot afford the high environmental and fiscal costs of enormously complex procedures. That just makes for expensive confusion -- confusion will inevitably find its way down to the working level of the program and to the scientific community undertaking the work and subsequently to the quality of work.

The opportunity to streamline the program, to maximize its impact, to assure adequate funding, and to give the damage assessment program clear and simple direction is before us. I would urge you to recognize the lessons of recent federal-state conflicts and address the many dimensions; the total dimensions of policy that can keep us working together.

FUTURE FEDERAL-STATE RELATIONSHIPS

Finally, we must look at our recent experiences in a broader context; what should be the nature of relationships between federal and state governments in the future? Our experience leads us to consider one of two directions. Either we engage in a more deliberate effort to establish an effective working partnership between federal and state entities; or we seek a total reordering of the traditional federal-state interplay.

I strongly suspect that the latter is the direction in which we ought to be heading in the long run.

Traditionally, state and municipal governments have looked to the federal government for answers. We have looked to the federal structure and sought to fit within it so that we could take most advantage of federal monies and programs.

In some areas, this traditional approach still works; but more and more, when we get into the question of developing policy, this approach is not necessarily the best one. And more and more, states are finding that the problems as we define them cannot and ought not be force-fitted to federal preconceptions of the problems.

It is within the states where critical problems are most vividly encountered. It is within the states where officials can be held most directly accountable. And it is within the states that the imaginative new approaches can be tried.

When we are trying to react to new and critical problems; when we are seeking to devise a policy, a new policy, that will meet the needs of citizens living within their own environments, we have got to stop simply trying to fit ourselves, with all our differing needs, within some federal umbrella. We must head toward a time when the federal government adapts its programs and monies to fit within the overall public policies of the states.

Such a dramatic change in governmental relations is clearly a long way in the future. For now, we must insist upon the immediate and highest standards of protection for the oceans. We must be capable of approaching the problems without this continual resistance to shared responsibility. And we must come to respond to the problems of pollution of the oceans with a vigor and policy as complex as the oceans themselves. We share common problems. We must share common responsibilities. I hope that the time has come that we now recognize this and act together.

OIL SPILLS IN THE UNITED STATES
THE STATISTICAL PICTURE

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As was stated in RADM Fugaro's keynote address (printed elsewhere in these proceedings) the past two decades have seen an exponential increase in the interest to preserve our environment. Public concern about oil spill catastrophies has grown as the media has communicated news of resulting socio-economic and environmental damage from spills such as the 1969 Santa Barbara spill, the TORREY CANYON, the METULA, the SANSINENA, and the ARGO MERCHANT spills.

Prevention has been identified as the key element in attaining the national goals of safe water by 1983 and clean water by 1985. Prevention has become the focus of the oil spill abatement program plans and research projects that abound today. Any study that addresses the national oil spill situation must have a data base as its foundation.

The objective of this paper is to provide such a foundation by presenting the general trends of spill frequency and volume by gallons over the past five years, placing particular emphasis upon 1977.

THE POLLUTION INCIDENT REPORTING SYSTEM (PIRS)

The Water Quality Improvement Act of 1970 established the Coast Guard's Marine Environmental Protection (MEP) program. Amendments to the Federal Water Pollution Control Act (FWPCA) in 1972 and 1977 greatly expanded the responsibilities of that program. Inspired by the national goal of prevention, a program objective was established. The objective was two-fold: to prevent and abate spillage pollution and to accomplish this in a cost-effective manner.

Executive Order 11548 names the Coast Guard as the agency responsible for receiving reports of all known spills of oil and hazardous substances. Therefore, whenever a spill is reported to, or discovered by, the Coast Guard, the spill is investigated.

Descriptive, response (cleanup) and penalty data is collected for each spill and stored in a computerized master file at Coast Guard Headquarters. The system which maintains the data is the Pollution Incident Reporting System (PIRS). The data has two purposes. First it is used to respond to frequent inquiries from a diverse group of users including Congress, Federal agencies, special interest groups, industry, academia and private citizens. Usually, these users want a general idea of the pollution situation for a particular location or to provide basic trend information. Most often, the data is used to provide a foundation for further analysis. Secondly, the data is used to assist the MEP Program Manager by providing a means of measuring Coast Guard performance while observing the spillage trends for each Coast Guard district, thereby measuring program effectiveness.

CONSIDERATIONS FOR DATA ANALYSIS

Since the Coast Guard has been authorized to collect data on every known spill in navigable waters, the PIRS file contains the most comprehensive data available. It is noteworthy that the file contains reported discharges only. It is estimated that approximately 80% of all spills are reported to the Coast Guard and recorded in the PIRS data base. Reported spills are a reasonable surrogate for actual spill trends and patterns.

It is also important to consider that through the prevention program, more spills are being discovered as a result of improved monitoring and surveillance. Additionally, the media has given attention to the spill problem which has caused an increase in the number of spills reported.

When observing the spillage trends, the location should be considered. The designation of a spill as minor, medium or major depends upon whether its location is coastal or inland:

	Inland	Coastal
Minor	0 - 999 (gallons)	0 - 9,999
Medium	1,000 - 10,000	10,000 - 100,000
Major	Over 10,000	Over 100,000

Unusual spills should be considered when drawing generalizations. For example: ARGO MERCHANT spilled 7.5 million gallons in 1976, and the HAWAIIAN PATRIOT spilled 9.6 million in 1977.

SPILLS BY WATERBODY

Frequency is a reliable trend indicator, since frequency cannot be skewed. Figure 1 shows frequency between 1973 and 1977 which has remained stable over the past five years. There has been a slight downward trend which is encouraging in light of increased reporting.

Volume is irregular as shown in Figure 2. Until 1977, there was a steady increase in volume. Omitting the HAWAIIAN PATRIOT spill, approximately 8.6 million gallons were spilled in 1977.

The charts in Figure 3 show the total picture for frequency and volume for the past five years. The Gulf has had the most spills, due to the tremendous traffic and the number of oil drilling platforms. Suprisingly, however, the inland area has typically experienced the greatest volume.

1977 is consistent with this trend (as shown in Figure 4). The Gulf had the largest number with 3,546 spills and the greatest volume was inland (by excluding the 9.6 million gallon spill). Figure 5 graphically shows the spill frequency and volume.

When considering locations, users of the data are often curious about the type of location. As shown in Figure 6, ports and harbors account for the greatest frequency with 33.3% of the total for 1977, closely followed by rivers and channels with 31.1%. Open coastal waters experienced the greatest volume, accounting for 57/9%. Without the HAWAIIAN PATRIOT spill, beaches and non-navigable waters had the greatest volume.

OIL SPILL DISTRIBUTION

The HAWAIIAN PATRIOT was the only spill over a million gallons (Figure 7). In fact, 36.7% of the 1977 spills were under 10 gallons which accounts for only 1% of the total volume. The reverse is also true. Spills over 100,000 gallons make up 1% of the total number of spills while constituting 70.3% of the volume. Figure 8 graphically depicts the distribution.

MATERIAL SPILLED

For 1977, the greatest number of spills involve crude oil and diesel oil making up 42% of the total. Crude oil experiences the most voluminous spills accounting for almost 70% of the total (over 12 million gallons as seen in Figure 9). Figure 10 shows the comparative number and volume of spills of oil and hazardous substances. Oil experiences approximately 80% of both frequency and volume.

TIME OF SPILLS

As seen in figure 11, between 1973 and 1977, most spills have occurred in the months of May, July and August. The greatest amount of oil has been spilled during January, October and December. By year, 1976 had the greatest frequency of spills and the greatest volume (as shown in Figure 12).

SOURCES

Most spills are vessel related. Figure 13 provides the frequency and volume for 1977. Vessels accounted for 33.1% of the frequency and 66.1% of the volume. Closer examination reveals that barges spilled more frequently than tankships in 1977, and excluding the 9.6 million gallon spill, barges spilled a greater volume (Figure 14).

CONCLUSION

The PIRS data base supplies the kind of data that is needed to provide a general picture of the United State's oil spillage situation. Such data is necessary to provide a foundation for further analysis. Past research and analysis have already proven to be beneficial in moving toward our goal of clean water by 1985. It has been a significant part of the prevention key that is needed to solve the water pollution problem.

Frequency

Oil — 1973 — 1977

	1973	1974	1975	1976	1977
INLAND AREA	1,509	2,700	2,350	2,105	2,079
ATLANTIC	2,756	3,037	2,865	2,269	2,372
PACIFIC	2,587	2,139	1,790	1,859	1,861
GULF	3,706	3,490	3,316	3,726	3,546
GREAT LAKES	384	371	489	778	762
TOTAL	10,942	11,737	10,810	10,737	10,620

FIGURE 1

Oil Spills by VOLUME

(in Gallons)

1973 — 1977

	1973	1974	1975	1976	1977
INLAND AREA	6,828,944	8,286,122	7,513,420	5,368,446	3,155,407
ATLANTIC	4,164,861	3,117,000	8,746,363	8,873,663	1,652,645
PACIFIC	633,852	459,830	870,689	1,615,838	9,965,875
GULF	3,433,425	4,260,497	4,275,163	7,052,490	2,529,906
GREAT LAKES	286,509	585,658	374,315	714,133	319,375
TOTAL	15,347,591	16,709,107	21,779,950	23,624,570	17,623,208

FIGURE 2

Oil Pollution Incidents by AREA

1973 — 1977

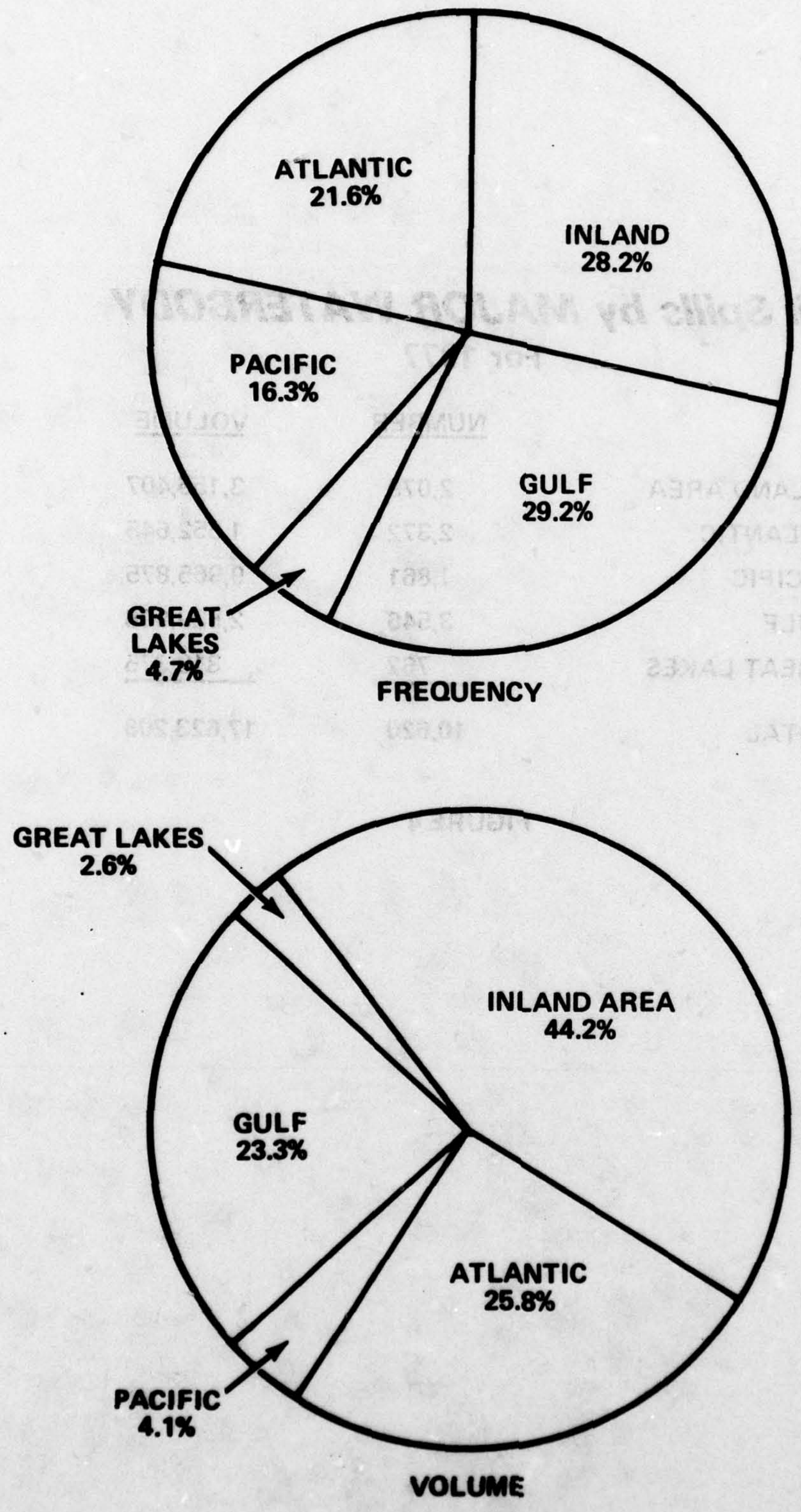


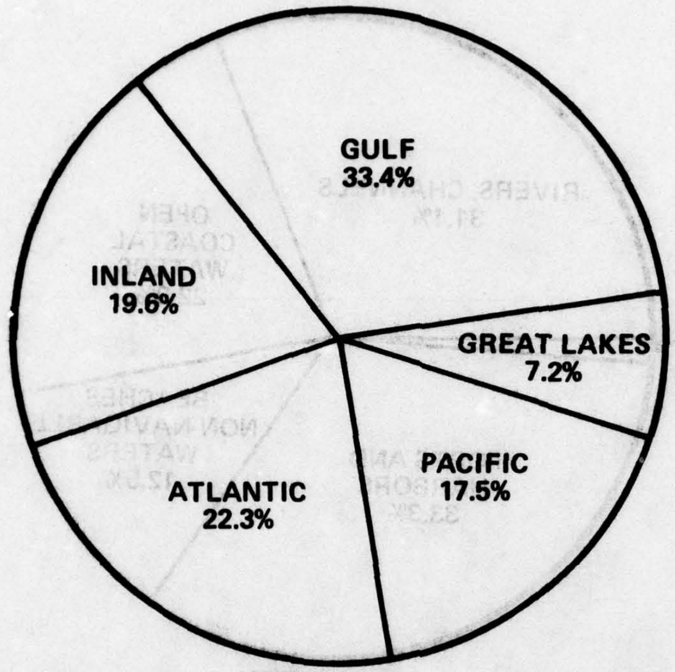
FIGURE 3

Oil Spills by MAJOR WATERBODY
For 1977

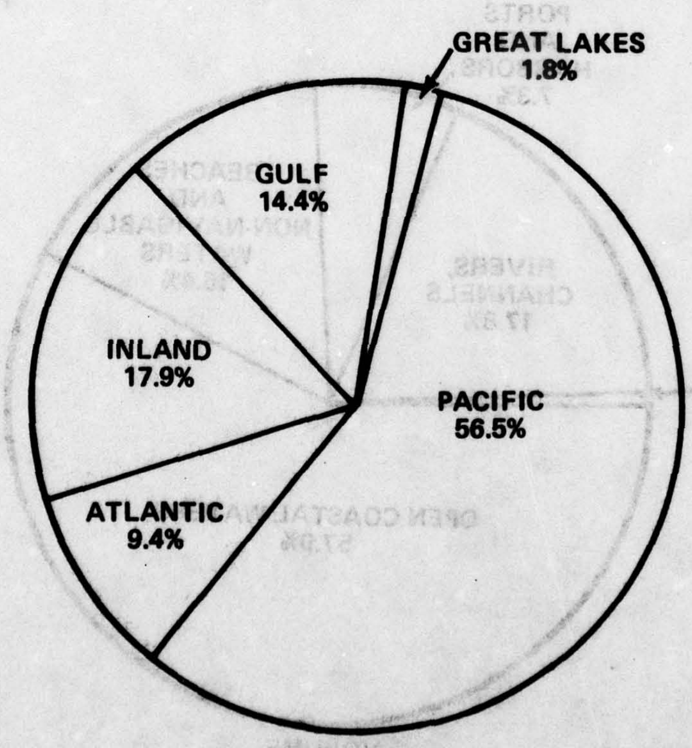
	NUMBER	VOLUME
INLAND AREA	2,079	3,155,407
ATLANTIC	2,372	1,652,645
PACIFIC	1,861	9,965,875
GULF	3,546	2,529,906
GREAT LAKES	762	319,375
TOTAL	10,620	17,623,208

FIGURE 4

Oil Spills by MAJOR WATERBODY
For 1977



FREQUENCY

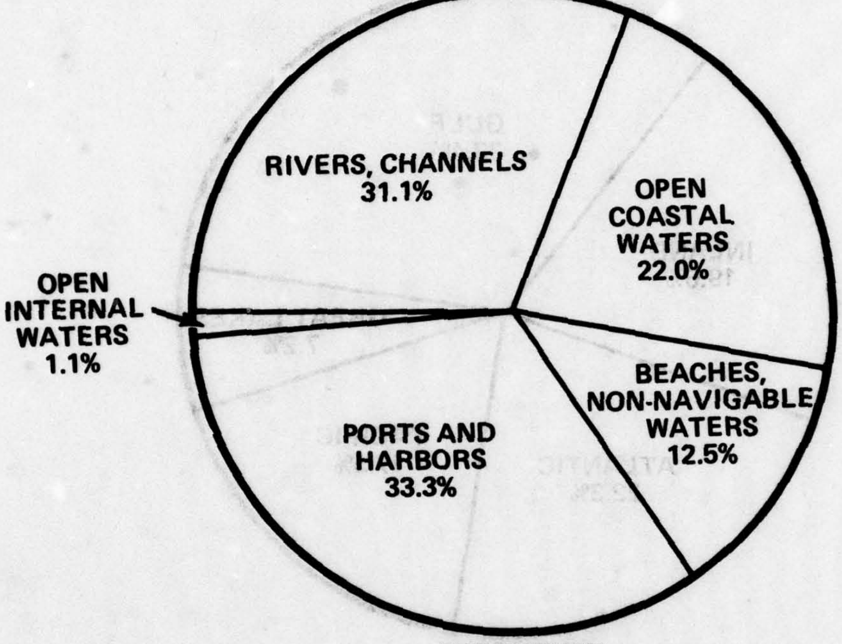


VOLUME

FIGURE 5

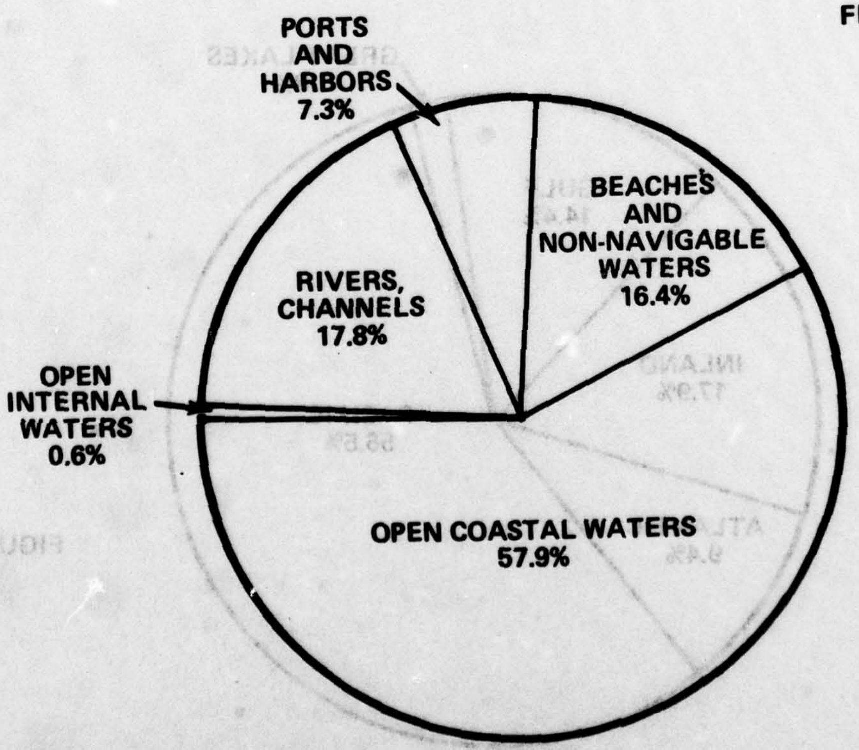
Type of Location of Oil Spills

For 1977



FREQUENCY

FIGURE 6



VOLUME

Oil Spill Distribution of
FREQUENCY AND VOLUME
For 1977

GALLONS	FREQUENCY	VOLUME
0-9	3,897	10,234
10-49	2,485	51,706
50-99	788	49,951
100-999	1,481	431,409
1K-10K	521	1,639,063
10K-50K	85	1,767,355
50K-1000K	30	4,073,490
OVER 1 MILLION	1	9,600,000
UNKNOWN	1,318	0
TOTAL	10,620	17,623,208

FIGURE 7

Distribution of Oil Spills by NUMBER and by VOLUME

1977

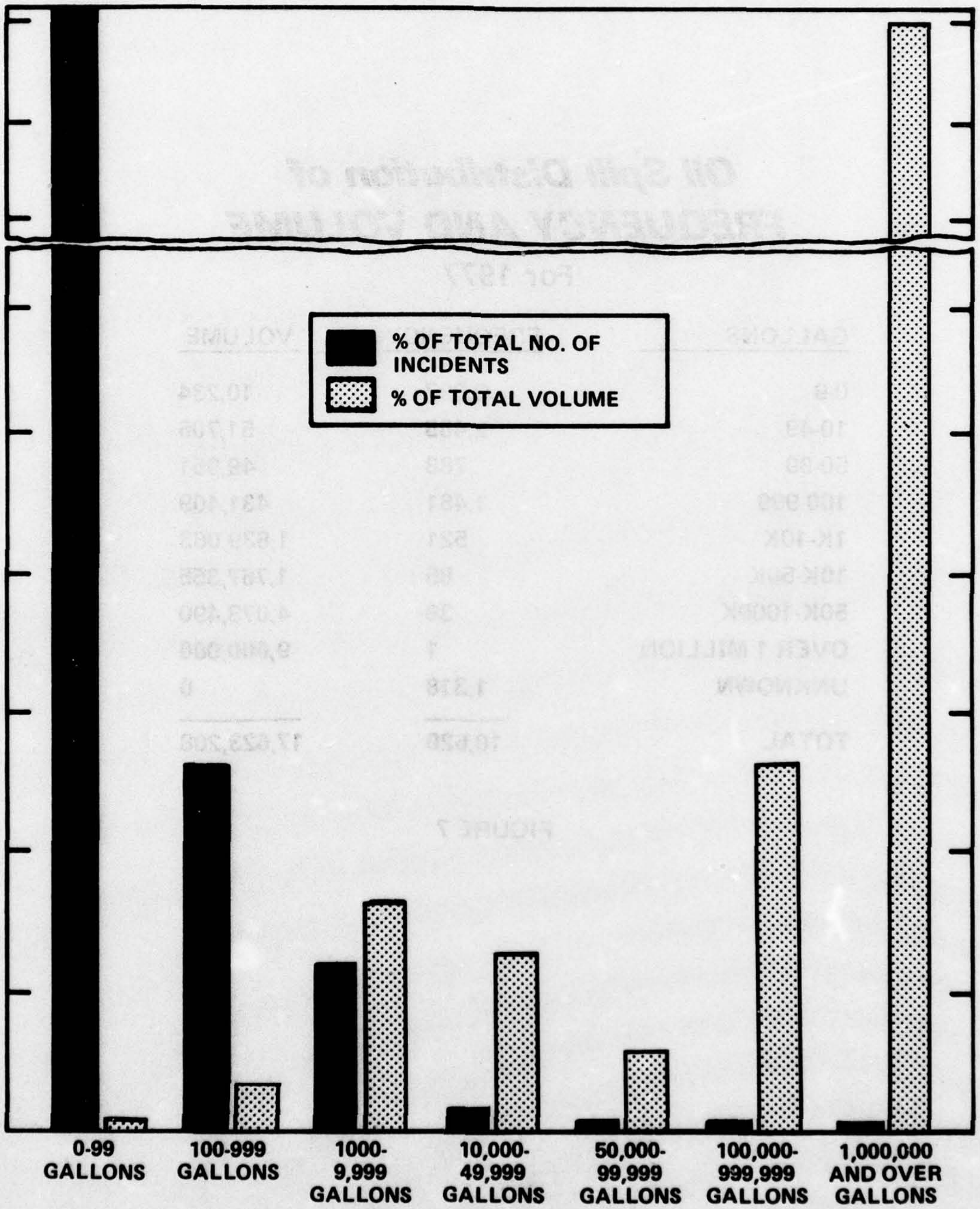


FIGURE 8

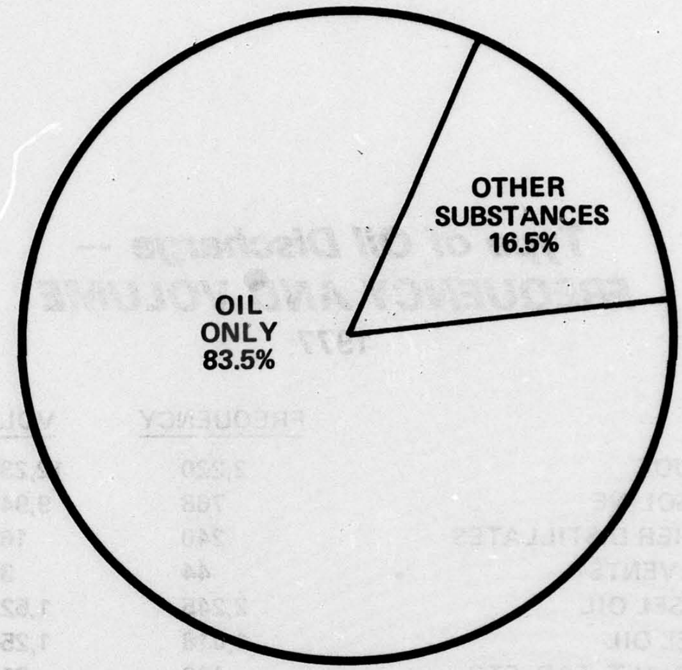
Type of Oil Discharge — FREQUENCY AND VOLUME
1977

	FREQUENCY	VOLUME
CRUDE	2,220	12,232,391
GASOLINE	768	9,947,776
OTHER DISTILLATES	240	163,570
SOLVENTS	44	30,561
DIESEL OIL	2,245	1,521,788
FUEL OIL	1,018	1,250,878
ASPHALT, TAR, ETC.	132	219,341
ANIMAL OR VEGTABLE OIL	67	108,025
WASTE OIL	1,350	517,636
OTHER OIL	2,536	584,242
TOTAL	10,620	17,623,208

FIGURE 9

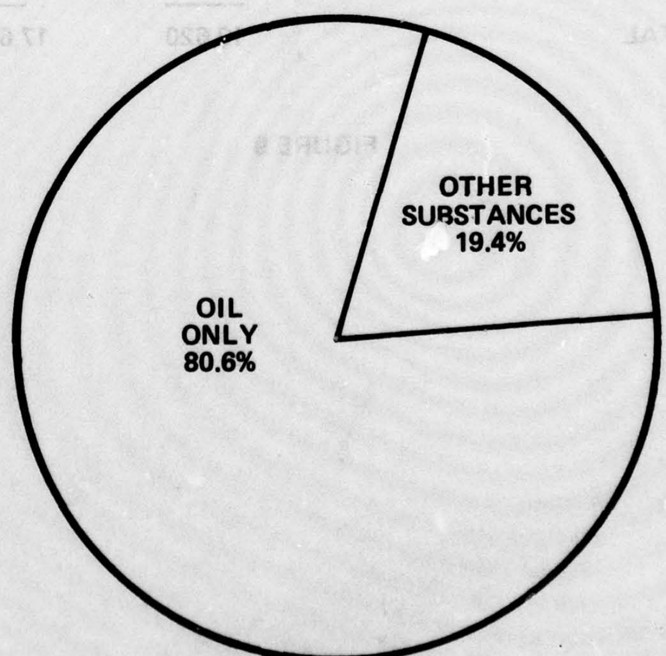
Oil vs Other Substances

1973 — 1977



FREQUENCY

FIGURE 10



VOLUME

Average Oil Pollution Incident by MONTH

1973 — 1977

	FREQUENCY	VOLUME (IN 1000'S OF GALLONS)
JANUARY	902	3,998
FEBRUARY	842	963
MARCH	941	1,866
APRIL	889	2,238
MAY	1005	837
JUNE	977	1,173
JULY	1014	950
AUGUST	1010	621
SEPTEMBER	939	440
OCTOBER	847	2,836
NOVEMBER	795	469
DECEMBER	803	2,621

FIGURE 11

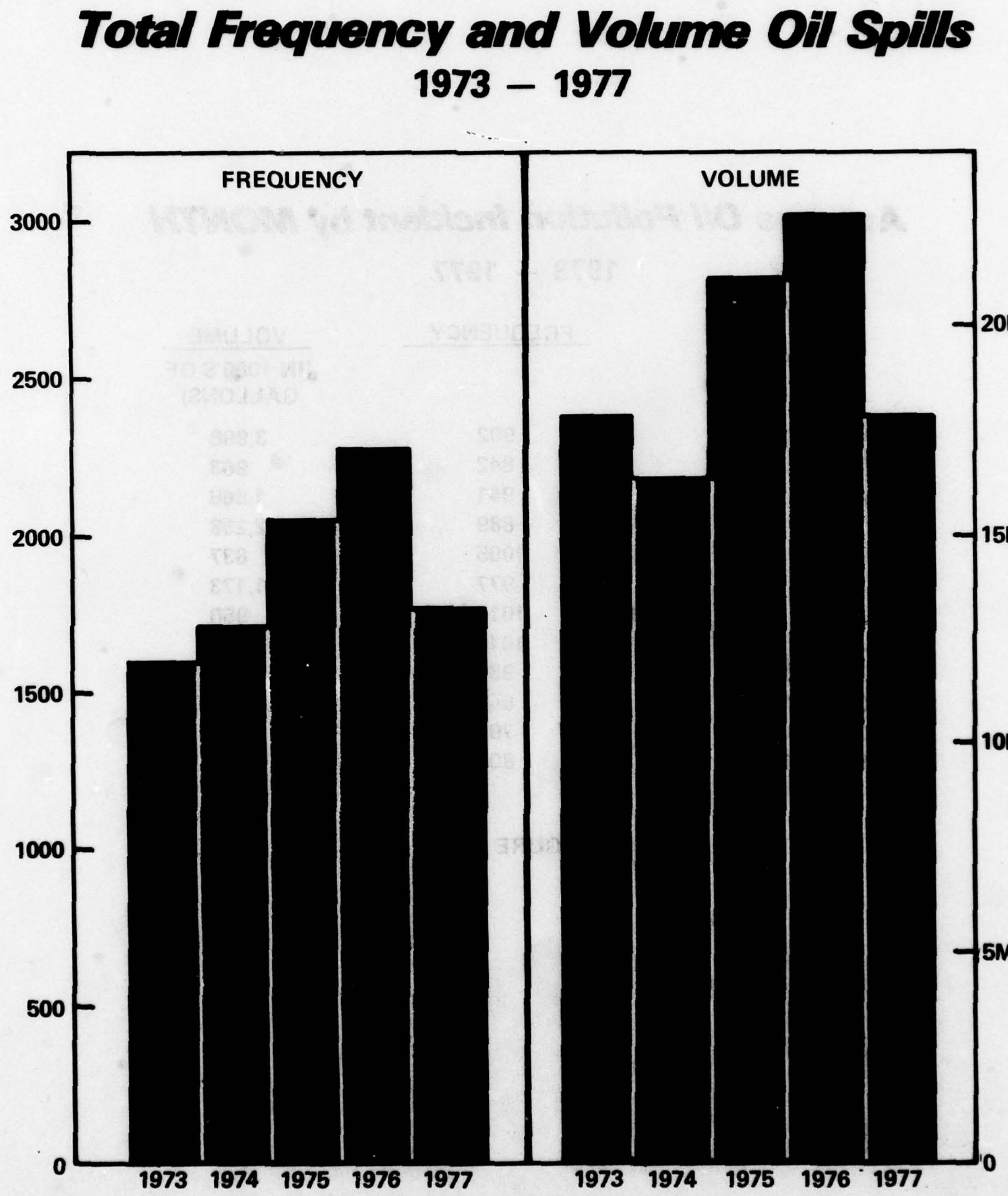

Total Frequency and Volume Oil Spills
1973 — 1977
FREQUENCY
VOLUME
3000
2500
2000
1500
1000
500
0
20M
15M
10M
5M
0
1973
1974
1975
1976
1977
1973
1974
1975
1976
1977

FIGURE 12

Frequency and Volume Oil Spills by SOURCE
1977

SOURCE	FREQUENCY	VOLUME
VESSELS	3,521	11,639,271
LAND VEHICLES	492	532,242
NON-TRANSPORTATION-RELATED FACILITIES	2,442	1,812,835
PIPELINES	481	2,498,025
MARINE FACILITIES	678	951,751
LAND FACILITIES	172	84,398
MISCELLANEOUS/UNKNOWN	2,837	592,567
TOTAL	10,620	17,623,208

FIGURE 13

Frequency and Volume of Vessel-Related Oil Spills
For 1977

	FREQUENCY	VOLUME
TANKSHIPS	535	9,808,048
TANKBARGES	1036	1,568,688
DRY CARGO BARGES	34	1,195
DRY CARGO SHIPS	364	71,060
COMBATANTS	179	12,412
OTHER VESSELS	1373	177,868
TOTAL	351	11,639,271

FIGURE 14

THE SOCIO-ECONOMIC-LEGAL ASPECTS OF OIL SPILLS

Chairman: PETER FRICKE
East Carolina University

THE COMPREHENSIVE OIL POLLUTION LIABILITY AND COMPENSATION ACT: AN UPDATE

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Washington, D.C. 20590

The opinions or assertions contained herein are the private ones of the author and are not to be construed as official or reflecting the opinions of the Commandant, the Chief Counsel of the Coast Guard, or the Coast Guard at large.

THE COMPREHENSIVE OIL POLLUTION LIABILITY AND COMPENSATION ACT: AN UPDATE

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ABSTRACT

Despite a number of highly publicized oil spills throughout the world, the legal system of the United States has been slow to respond to the need for strict liability and expedited claims procedures for persons whose property or livelihoods are injured by oil pollution. Government sanctions against the discharge of oil have increased consistently, however, only recently has there been a Federal recognition that new remedies are required for the private citizen and for damages to natural resources. A number of bills are presently pending before Congress which provide a comprehensive and uniform oil pollution liability and compensation system. Though the bills differ in many particulars, a broad outline of their provisions is useful to project the influence of such a bill on the legal liabilities of spillers, the compensation available to parties injured, and on natural resources damaged by oil pollution.

BACKGROUND

In March 1967 the TORREY CANYON ran aground off the Coast of England, spilling 117,000 tons of crude oil on the beaches of France and England, and focusing international attention on the problem of damages from oil pollution. In January 1969 the discharge from the Santa Barbara Platform "A" spread an estimated 20,000 tons of crude oil on Southern California beaches and parks. The ARGO MERCHANT ran aground in December 1976 on Nantucket Shoals discharging its entire cargo of 28,000 tons of oil into the North Atlantic, damaging the ocean resources in the vicinity, yet mercifully missing the shores of New England. Catastrophic spills, as well as moderate and minor oil spills from vessels and facilities, have continued in the United States at a rate of approximately 10,000 per year, and have taken their toll in damaged natural resources and losses to the economy.[1]

As plaintiffs entered U.S. courts of law as individuals, and later as classes, the common law legal system proved to be a time-consuming, expensive method of recovery. Under legal theories of negligence, trespass, and nuisance, certain types of plaintiffs and damages were denied compensation altogether.[2] Direct damages from oil pollution to real or personal property have been recognized; in general, annoyance, discomfort, and economic losses have not been compensated.

Statutory solutions to the problem of assuring compensation to parties injured by oil pollution have been slow in coming. After statutory prohibitions on the discharge of oil became commonplace in the United States,[3] the first substantial statutory civil liability to be imposed on a spiller of oil was for reasonable government cleanup costs in the Clean Water Restoration Act of 1966. This liability applied only to vessels, in the "coastal navigable waters of the United States."[4] However, the liability of a vessel for cleanup and other damages from oil spills was severely limited by the Limitation of Liability Act of 1851.[5] In the 1970 Water Quality Improvement Act, liability for actual government oil pollution cleanup costs was established for all spills from vessels and facilities. This liability was also extended from the coastal waters of the United States to the navigable waters, and the contiguous zone in the WQIA of 1970.[6] The liability limitation of a vessel owner for government cleanup costs was set at the lesser of $100 per gross ton or $14 million for vessels and up to $8 million for facilities. The government's ability to recover civil penalties for oil pollution was strengthened by the provisions of Federal Water Pollution Control Act Amendments of 1972 and liability for government cleanup of hazardous substances was added.[7] Finally, in the Clean Water Act of 1977, liability limits for vessels and facilities were substantially increased and some provisions were added to permit government recovery for damage to natural resources.[8]

While statutory prohibitions against oil pollution, and liability for government cleanup costs increased in severity, the position of the private citizen whose property or livelihood was damaged by the pollution remained substantially the same in 1978 as it had been in 1899.

In the Trans-Alaskan Pipeline Authorization Act of 1973,[9] the basic concepts for oil pollution liability and compensation for private damages were established in Federal law. Persons damaged by oil pollution from TAPs vessels could recover from the vessel (up to $14 million) or a TAPs

fund (up to $100 million) on a strict liability basis. However, Congress did not specify the recoverable damages or claims procedures in great detail. Furthermore, no recovery beyond the $100 million fund was permitted. This basic approach was followed in 1974 with the Deepwater Port Act[10] where a vessel discharging oil was made strictly liable for damages up to $150/gross ton (with a $20 million ceiling) and the deepwater port facility would be liable up to $50,000,000. Congress did not specify categories of damages in this Act either, though the statute indicated that a broadening of the common law rules was favored. The Deepwater Port fund, like the TAPs fund would be sustained by a fee levied on oil from the enterprise and would be available when damages exceeded the spiller's liability limits or the spiller had a legal defense to liability.

Yet neither of these public laws covered any of the private damages resulting from the 10,000 oil spills that occur annually, for the first deepwater port has yet to be built and TAPs has only recently begun pumping oil from the North Slope to awaiting vessels.[11] A plethora of state laws with varying provisions, and with varying degrees of effectiveness was passed beginning in the early 1970s to address the problem of private damages from oil pollution. These state and Federal laws have created a patchwork of remedies for the individual damaged by oil pollution.

The Deepwater Port Act of 1974 in §18(n) mandated a study by the Attorney General of methods and procedures for implementing a uniform law providing liability for cleanup costs and damages from oil pollution of the ocean. The study was published in July, 1975 by the Senate Commerce Committee[12] and furnished some of the groundwork for the first comprehensive oil pollution liability and compensation bill, H.R. 9294, proposed by the Ford Administration and introduced in the 94th Congress.

The Ford Administration bill did not fare well in either House of Congress. Since the bill combined a domestic compensation title with two titles implementing the IMCO Civil Liability[13] and Fund Conventions,[14] the proposal ran aground in shoalwater. The Civil Liability Convention liability limits for vessels were perceived as too low. During the 2d session of the 94th Congress, the House Merchant Marine and Fisheries Committee reported out H.R. 14862, a domestic oil pollution liability and compensation bill that adopted many of the recommendations of the Attorney General's study.[15]

The 95th Congress and a new Administration were launched into an oil-covered sea of troubles upon arrival in Washington in January 1977. The ARGO MERCHANT had broken up on December 15, 1976 followed in quick succession by the explosion of the SS SANSINENA on December 17, the groundings of the SS OLYMPIC GAMES and the SS DAPHNE on December 27 and 28. The vessel losses continued with the disappearance of the GRAND ZENITH around January 4, 1977 and sinkings of the U.S. tank vessel CHESTER POLLING on January 10 and the IRENES CHALLENGE on January 17 in the Pacific. President Carter immediately established a task force to study the problem of oil pollution of the oceans, and thereafter transmitted his oil pollution initiatives to Congress on March 17, 1977.[16] A high priority initiative was the passage of a uniform oil pollution liability and compensation bill. An Administration bill, S. 1187 that closely tracked H.R. 14862 from the previous Congress, was sent to Capitol Hill the same day. Due in large measure to the tanker accidents, Congress was already at work trying to rectify the maze of contradictory "international, federal, and state oil spill liability laws.....with gaps in liability so wide you could drive a Liberian tanker through them, even without a functioning gyrocompass."[17]

The House of Representatives, after consideration by the Merchant Marine and Fisheries Committee[18] and the Public Works and Transportation Committee,[19] passed H.R. 6803 on September 12, 1977.[20] On the same day, the Senate Committee on Commerce, Science and Transportation, reported out a new bill, S. 2083.[21] The other congressional committee with jurisdiction over the subject, the Senate Environment and Public Works Committee, failed to act because it was tied up during much of the session in considering the Clean Water Act of 1977 and the Clean Air Act of 1977. The comprehensive oil pollution liability and compensation bills that had been passed or reported were carried over to the 2d session of the 95th Congress.

The Senate Committee on the Environment and Public Works held hearings on the subject on April 17-18, 1978, a few days after Senator Muskie had introduced his own bill, S. 2900, a "superfund" bill for both oil and hazardous substances.[22] The Muskie bill is different in many respects from the Administration bill, S. 1187; the House bill H.R. 6803; or the Senate Commerce Committee bill, S. 2083. Because of these differences, the legislative waters remain unclear at the present time. However, the pending bills have enough in common that the general outlines of a future "Oil Pollution Liability and Compensation Act" may be the subject of prospective analysis.

THE PURPOSE OF OIL POLLUTION LIABILITY AND COMPENSATION LEGISLATION

Each of the bills listed above has as its purpose the establishment of a comprehensive system of liability and compensation for damages caused by oil pollution in the waters of the United States, the contiguous zone, and in high seas areas where U.S.-managed resources are damaged. The bills each impose strict liability for oil pollution damages on the owners and operators of the sources of oil discharges, and each bill creates a backup fund to compensate claimants who are not compensated, for whatever reason, by the source of the pollution.

The strict liability system established by these bills would overcome two of the most serious barriers to recovery that plaintiffs have encountered under the common law: (1) inability to prove negligence of the spiller, and (2) inability to prove that the resultant damages are special, proximately caused by the oil pollution, or foreseeable. In place of these two difficult-to-prove elements of a traditional tort recovery, the bills require only (1) that the vessel or facility be the "source" of the oil discharge and (2) that any of 7 broad classes of damage claims resulted from the oil pollution. Indeed, in the case of oil pollution damage from an unknown source, the bills provide that only the second element need be proven to recover from the fund.

STRICT LIABILITY OF SOURCE - CLAIMS PROCEDURE

Obtaining proof of the "source" is becoming increasingly common due to public awareness of the oil pollution problem, the FWPCA duty to notify the Coast Guard of an oil discharge,[23] and the increasing availability of sophisticated spill detection and "oil fingerprinting" analysis. Claimants under "superfund" need no longer prove that the spill was the result of a negligent act of the vessel or facility. The spiller would be notified by the Secretary of Transportation that he is the "designated source" of oil pollution, and unless the designation is denied, the spiller would begin advertising procedures for submitting claims and begin accepting claims and negotiating settlements for resultant oil pollution damages.[24] Liability of the designated source does not depend on proof of fault or negligence.

Should the spiller and the claimant be unable to agree on a monetary settlement for the damages sustained, or should the spiller reach his legal liability limit, the claimant may present his claim to the superfund. Private claims adjustors under contract to the superfund would have

the authority to make reasonable settlements on the spot. Should claimants be damaged by oil pollution from an unknown source, or should the spiller have a legal defense to liability, claims advertising and initial settlement negotiations would be conducted by the superfund.[25] The fund's liability is unlimited, thus assuring every claimant of full recovery of actual damages.

WHAT TYPES OF DAMAGES ARE COMPENSABLE?

The codification of the types of damages that will be legally compensable eliminates, in part, the second difficult traditional element of tort proof, that of special damages, proximate causation, or foreseeability. Under prior common law, claimants under a nuisance theory had to prove special and particular damages, different from those of the general public; negligence claimants not only had to prove negligence, but "proximate causation" and foreseeability of damages. Under the common law therefore, owners of pleasure boats were denied recovery for the loss of use of their boats because the injury was intangible and no different than the general public's loss of use of the polluted area.[26] The economic loss and annoyance sustained by non-riparian property owners has also been held to be not compensable, because there was no physical injury to the property from the oil spill.[27] In numerous cases a significant class of non-beach front property owners, whose sun and sand worshipping clientele stayed away, were denied recovery for their economic losses because, unlike the beach-front property owners, their losses were "indirect." While the right of boat-owning, commercial fishermen to recover economic losses from the injury to the commercial fishing grounds by oil pollution has achieved general legal recognition, the right of an employee on a fishing boat to recover lost wages has met with divided judicial opinions.[28] Except for the commercial losses of fishermen and riparians, courts have been reluctant to allow recovery of lost profits by businessmen, on the rationale that the non-riparians did not directly use the polluted body of water,[29] and that reduced profits of a business activity are too speculative for recovery.[30] Finally the legal status of a state's claim to oil-damaged resources or lost tax revenue due to oil pollution has not achieved judicial recognition.

Under the "superfund" legislation each of the damages relating to costs, injuries or losses listed below would be compensable without a showing of foreseeability or unique damages if the damage is due to oil pollution:

(1) removal costs;

(2) injury to, or destruction of, real or personal property;

(3) loss of use of real or personal property;

(4) injury to, or destruction of, natural resources;

(5) loss of use of natural resources;

(6) loss of profits or impairment of earning capacity due to injury or destruction of real or personal property or natural resources; and

(7) loss of tax revenue for a period of one year due to injury to real or personal property.[31]

Since the assessment of damages is the central theme of this conference, an extended discussion of each type of compensable damage is appropriate. Unless otherwise noted the discussion refers to the formulation of damages set out in S. 1187 and H.R. 6803.

Removal Costs.[32] The Federal Government may claim against the spiller all actual removal costs incurred by, or on behalf of, the Federal Government under §311 of the FWPCA, and other oil pollution "cleanup" statutes.[33] As a practical matter, the Federal Government will incur these costs as a direct obligation of the superfund, which, in turn will claim against the spiller by subrogation. Individuals may also claim for reasonable cleanup costs. Owners of real or personal property may also recover for the reasonable value of their own labor in cleanup actions, though a thorough documentation of these efforts will undoubtedly be required. It is interesting to speculate whether this provision will provide an incentive to the legions of cleanup workers who have heretofore toiled in major spills as "volunteers."

Cleanup costs also include those costs incurred after a spill to prevent further pollution from occurring. Under certain conditions the discharger himself may recover his own cleanup costs in order to provide an incentive for rapid and thorough cleanup even if the discharger believes he has a legal defense to liability. The increased certainty of recovery of reasonable cleanup costs should result in more rapid cleanup by both the spiller and potential claimants.

Injury to, or Destruction of Real or Personal Property.[34] This type of damage will be recoverable by any claimant, including Federal state, or local governments, if the property or natural resource is directly utilized by the claimant in the course of his business. The term "property" is defined to mean only real or personal property that is littoral, riparian, or marine in nature, including boats.[35] Under this section the diminution of value of real property or personal property such as nets, lobster pots, and boats could be asserted in a claim. Lessees of property may recover their losses as well as the property owner. Though S. 2083 and S. 2900 do not limit the definition of "property" as in S. 1187 and H.R. 6803, the requirement that the property be damaged or destroyed is tantamount to requiring that it be directly affected by the water which bears the pollutant.

The measure of damage to real or personal property could be computed in many ways. For real property, the cost of full on site cleanup plus the remaining diminution of real value of the property might be an appropriate measure of total damages for the owner. A study of property values after the Santa Barbara spill disclosed a 15% temporary diminution of sales value of beach-front properties.[36] For lessees of real property, the value of the oil pollution loss would be the diminution of the rental value.

Fishing vessels which are "trapped" in a harbor behind a protective boom during an oil spill may face a choice between incurring actual damages to the boat and nets from oil on the way to other fishing grounds, or losing profits by remaining in the harbor. During the Santa Barbara spill some boats remained in the harbor, others sought distant fishing grounds. The fisherman who makes a good faith decision should be able to recover for actual damages whatever his decision.[37]

Loss of Use of Real or Personal Property.[38] This category of damages is one that was often not compensated under "common" law. In the Santa Barbara spill case, pleasure boat owners recovered for the damage to their boats, but not for the "loss of use" of the boats. The court stated that they were deprived of no more than their "occasional Sunday piscatorial pleasures."[39] Under each of the superfund bills, the owner's loss of use of a pleasure boat, or the temporary loss of use of his beachfront property, is compensable even without any real, out-of-pocket loss or permanent loss of value. The likely measure of damages will be the reasonable rental value although the pro rata cost of maintaining the real or personal property during the period of

non-use (taxes, interest, dock fees, etc.) might also be used. Whether the "Sunday picatore" or the weekend beach-goer will recover the rental value for a month of Sundays only or for an entire month is a question that may arise in adjudication of claims under superfund. The question whether the fair rental value of the pleasure boat should be reduced by a setoff for the out of pocket expenses the "Sunday piscatore" did not incur in highway tolls and gasoline on the way to the shore, may also arise. It should also be noted that loss of use of non-riparian property is not compensable under superfund, though the non-riparian's loss of use may be identical to that of his riparian neighbor.

Injury to, or Destruction of Natural Resources.[40] Claims under this category of damages must be made by the President for U.S.-managed natural resources, and by a State for natural resources within the State or controlled by the State. Oil pollution damages to a state-owned park could be asserted under this category, or by the State as "owner" of the park. The primary benefit of this category is to have the spiller compensate society for losses of the "ferae naturae" -- those natural resources, whether harvestable or not, that are not "owned" by any person. The President would claim any losses to the fish stocks, coelenterata, crustacea, mollusks, and sponges managed under the Fishery Conservation and Management Act.[41]

A State may claim for lost or damaged natural resources, such as clam or oyster beds, or fish within the state's marine boundaries, in addition to natural resources that may not have an economic harvesting value. This provision codifies the type of claim made by the State of Maine in the TAMANO case as "trustee for the citizens of the State of Maine of all actual resources lying in, on, over, under and adjacent to its coastal waters."[42] The position of the State as "parens patriae" of state resources used or enjoyed by its citizens establishes the state's standing to sue. Though courts have been asked to reject such claims as "too speculative", passage of a superfund bill should silence this argument. The possibility of double recovery, once by the State as "parens patriae" and also by the individual claimant harvesting or using the resource, is precluded by the superfund legislation. The harvester or user of the natural resource would recover only for lost profits while the trustee would recover for the "corpus" of the trust - the value of the resources themselves.

A unique feature of recovery of this item of damages is that the compensation paid by the spiller, or by the fund "shall be used only for the restoration of the natural resources damaged or for acquisition of equivalent resources."[43] Because many natural resources cannot be replaced, this provision may be interpreted to limit or even eliminate recovery. If acquisition of equivalent resources is not possible, the costs of whatever restoration is possible may not reflect the true social costs of the damaged resources. Recovery from the spiller or the superfund may be limited to the lower value because of the statutory limitation on the use of recovered funds. If acquisition of equivalent resources is attempted, can it be said that a few sunken liberty ships is in any sense the equivalent of a damaged coral reef, or hundreds of thousands of young fish from a fish hatchary the equivalent of millions of mature fish and eggs destroyed? Even if replacement is possible, the wisdom of taking resources from one area to replace the resources at another area is questionable and does nothing to eliminate the net ecological loss.

If the damaged or destroyed natural resources were truly irreplaceable, recovery under the proviso would be zero, for the invaluable resource would have no legal value. The proviso that appears in three of the superfund bills should not be a limitation on the amount recovered, and should be broadened to provide more discretion in the use of funds recovered for damaged or destroyed natural resources.[44]

Another potential issue that may arise in connection with damages to natural resources is whether setoffs against damages will be permitted for environmental benefits conferred by either the spill or the cleanup activity of the spiller. In the process of cleanup, the spiller may take action that increases the economic productivity of a waterway. There is speculation that such a setoff may be claimed in a Chesapeake Bay spill when the removal of oiled marsh grass increased oyster bed productivity. If, in the process of cleanup of a State Park, the spiller removes unsightly storm debris in addition to oil soaked debris, should a setoff be allowed?[45] Since the superfund concept requires payment only for actual damages, such an setoff might be allowed in appropriate cases.

There is an inherent cost/benefit decision to be made by a spiller when he negotiates with a claimant, as to whether he should (1) undertake further cleanup and restoration to decrease damages or satisfy a particular claimant or (2) pay damages to the claimant. If a few truckloads of sand for a private beach will satisfy a claimant, the spiller may elect to undertake the expense of extra cleanup or mitigation, rather than make a direct payment for damages.

Loss of Use of Natural Resources.[46] This item of damages will permit recovery for economic losses for those who exercise a public or private right to use the natural resources in the normal course of business. This category of damages will permit compensation to the subsistence fishermen, such as Alaskan natives, whose income has not been diminished by the lost resources, yet whose actual loss is no less real. The limitation of S. 1187 that the natural resources be used in the course of the claimant's business should not foreclose the subsistence users in a barter economy. Similarly, the individual who merely sets out a few lobster pots for personal consumption, or the "Sunday only piscatore" would be able to recover the fair market value of his lost catch assuming he could meet the "use in business" test. However, the question of setoffs once again may arise to eliminate the possible compensation to the "Sunday piscatore." Since the lost value of the "fish that got away" due to the oil pollution is, in most cases, greatly exceeded by the expenses incurred in fishing, he may not recover under this category. However, under the category of loss of use of real property, he may recover the fair rental value of the vessel itself, thus providing in real and measurable economic terms, some compensation for the aesthetic damage of a lost opportunity to "enjoy nature."

A unique feature of H.R. 6803 and S. 2083 is that the claimant need not use the natural resource in his business to recover damages as S. 1187 requires. Thus, the casual user of the beach, the tourist, could conceivably recover upon proof of actual economic loss. The renter of non-riparian property near the beach may recover the fair rental value and other expenses of a ruined vacation. However, the assertion of setoffs for many non-business claimants may reduce actual damages to zero.

Loss of Profits or Impairment of Earning Capacity Due to Injury or Destruction of Real, or Personal Property or Natural Resources[47] The categories of persons who may make claims under this category is large. All persons sustaining indirect economic losses from an oil spill may claim against the spiller or the fund. In order to recover damages the claimant's loss must be "due to "[oil pollution that results in] injury to, or loss of...property or natural resources."[48]

Two bills pending, S. 1187 and H.R. 6803, limit this class of claimants by requiring that 25% of the claimant's income must have been derived from the property or natural resource injured by the oil pollution. S. 2083 and S. 2900 contain no such limitation. The 25% requirement is not intended to limit claimants with small amounts of damages;

it denies these indirect economic claims when the loss of business income derived from the damaged property or natural resources, is not a substantial percentage of the total income of the business. The nautical supplier, the fish processing plant, and the chandler may claim for lost income or profits if 25% of the income was derived from the fishing vessels affected by the oil pollution or temporarily fishing elsewhere. Beachfront businesses reliant on the beach tourist trade will qualify. However, if the business makes a substantial part of its profits from property located in areas unaffected by the spill, it would be virtually impossible to distinguish between normal business reverses and the oil spill effects even if the business is located in an area affected by oil pollution. The department store 100 miles from the polluted beach may lose some sales of swimwear, though swimwear is but a small percentage of the profits of the business. There is reason to believe that the national recession rather than the oil spill may have caused some of the economic losses from decreased tourism in the Santa Barbara area.[49] This difficult question of causation becomes more complex when the oil spill is not a major publicized spill. The 25% limitation tends to remove from the claims process some of the difficult questions of causation, while compensating the claimants with substantial indirect economic losses from oil pollution damage to resources or property.

The non-business claimant who has lost income may also recover for lost income. The bellhop at the coastal hotel, the beachfront restaurant waitress, or hired hand on a fishing vessel may recover economic damages subject to the 25% limitation. Questions concerning alternative sources of income and mitigation of damages by other employment may arise, but the superfund bills establish a right to compensation where the common law has previously been niggardly. If the 25% requirement is met, something in the nature of a presumption may arise, that the economic loss was caused by the oil pollution.

A few examples will illustrate the operation of this category and the 25% limitation. The gas station owner on the interstate highway, 100 miles from the beach experiences a decrease of 10% of his income during the summer months, arguably because the beach tourist trade has fallen off due to an oil spill. The gas station owner five blocks from the beach hit by oil pollution has lost 45% of his previous years income. Based on provable facts, 50% of the beach gas station's gross income is derived from non-residents -- tourists with out-of-state licenses. The interstate owner can only prove 5% of his customers were bound for the beach. Because both of these economic injuries is indirect, it is

impossible to determine if the beach pollution caused either loss of income. However, in the absence of other causes for the lost income, only the service station owner near the beach will recover his damages under S. 6803 and S. 1187. Under the other two bills S. 2083 and S. 2900 both station owners could recover if a causal relationship could be proved between the pollution on the beach and the lost income. A more difficult causal question may be presented if the beach gas station sustained only a 10% loss of income, while the interstate state suffered a 45% drop. If the beach gas station could meet the 25% requirement, he would recover his 10% loss. The interstate station owner would have a difficult burden of proof. Though the arbitrary nature of the 25% requirement may be criticized, it does bear some relation to provable causation and relative economic impact and will ease the administration of claims. The fact that most claims will be settled extrajudicially will encourage payments in borderline cases.

A second difficult problem that will be encountered is to determine what entity may be a claimant and what period of lost income would be required for purposes of the 25% limitation. An example will again clarify the problem. A fast-food chain has one beach front outlet, near the site of a spill, which makes 75% of its gross income from tourists. The chain has 1000 outlets in other unaffected places across the country. If the one outlet suffers a 50% decrease in profits for the summer, should compensation be denied because the national corporation that owns the outlets relied on the beach resources for only a 0.1% of its profits? The answer to this question may hinge on State and federal standards for determining legal "persons", entitled to sue. Another actual example that may pose some difficulty is the claim of the State and local governments in California for the income from State Park admissions fees that were lost due to the Santa Barbara spill. The percentage of the State's total income lost was slight, however, if either the individual parks, or the parks administration agency of the government is the claimant, the 25% limit may be met.

The question of the permissible time period for determining the application of the 25% limit will pose problems. If the 25% requirement is met by the income from one summer tourist season, yet the profits from the unaffected winter season which do not rely on the affected natural resource reduce the percentage of profits relying on the natural resource to 10%, what period of time should govern? Under this example, a construction that will effectuate the primary intent of Congress would permit recovery based on a reasonable period of time, such as a tourist season or harvesting season.

The 25% requirement represents a compromise among conflicting policy considerations. While all real economic damages should be compensated, whether direct or indirect, it is often difficult to distinguish the economic effects of the pollution from business fluctuations and other causes. Economic effects of oil pollution may be felt hundreds of miles away from the actual site of the pollution, yet if substantial reliance on the affected property or natural resource and direct causation between the spill and the loss is shown, the superfund bills establish a right to recover losses.

The question of setoffs will also arise in connection with claims for lost income. The waitress who is laid off due to decreased tourist trade may take on other employment. If a claim is made, only the lost income may be claimed. If a fishing vessel is employed in cleanup operations, the owner and crew will recover only to the extent the lost income from fishing exceeds the substituted income from cleanup.

Loss of Tax Revenue for One Year Period.[50] This type of economic injury is one that has not yet been judicially recognized. Under the superfund bills state, local, and even foreign governments may claim against the spiller or the fund for lost tax revenues. Though this element of damage is relatively straightforward, the issue of setoffs may arise in a claim for lost taxes. The state revenue lost in sales taxes or motel bed taxes in one beach front area, may be regained by increased sales from nearby unaffected beaches which reap increased tourism. The affected motels and businesses would recover for actual losses due to the pollution, yet the state may have no net loss. Setoffs are not addressed by any of the pending bills, though presumably since only actual damages are to be compensated, setoffs would be permitted for all types of damage.

Damages not Compensable. A significant omission from the list of damages under the superfund bills is the costs incurred in reasonable efforts to prevent damages to natural resources. After every major spill, legions of volunteers and officials expend time, effort, and funds in an attempt to save oiled birds. In the METULA spill in 1974 there was much concern over the scheduled annual migration of penguins of the area of the spill, and some consideration was given to attempt to excluding the penguins from spill areas. These costs do not fit neatly into listed categories of damages in the superfund bills. If these efforts are undertaken by or on behalf of a business that uses the natural resources,

it could be characterized as loss of profits. However, if undertaken by the state in its capacity as trustee or by "volunteers", the superfund bills do not compensate for the protective actions undertaken. Similarly, there is no incentive for the spiller to take such action, because it is not a credit against his liability limit.

A like situation exists where the owner of personal property takes action not amounting to "cleanup" in order to prevent damages to property. The pleasure boat owner who hauls his boat to avoid oil pollution damage may find that he cannot recover his damage prevention costs, though he could have recovered his costs of hauling an oil soiled boat after the spill had wreaked its damages. The owner of a fishing boat who takes the same action may recover under the category "loss of profits".

None of the superfund bills compensate for "insult to the environment", "psychic damages" to persons or states, except through the listed categories of damages. The tourist who foregoes his enjoyment of nature, or the ornithologist whose subjects are killed by oil, is not directly compensated. However, the economic consequences of the tourists decision are compensated, and the state may recover for lost or damaged resources. The liabilities imposed by the superfund bills exceed those of prior law and more nearly reflect the social costs of the spill. The superfund proposals are a major step foward in the law concerning oil pollution damage compensation.

OTHER PROVISIONS

In all cases where the source of the oil pollution is known, the Secretary of Transportation will designate the responsible party who, if he does not deny the designation, will then advertise the procedures for submitting claims. Denial of the designation will be legally defensible if (1) he is not the "source" of the pollution; (2) the spill was caused solely by an act of God or an act of war. If the designation is denied for any reason, the superfund will advertise and claims will go directly to the superfund.

The spiller who accepts the designation may reach his limit of liability, and refer all other claims to the superfund. The limits of liability differ in each of the bills, but in general, the spiller's liability for all removal costs (including his own reasonable cleanup costs) and damages will be as follows:[51]

A vessel carrying oil in bulk as cargo	300/gross ton with minimum $250,000
A vessel not carrying oil in bulk as cargo	$150/gross ton
An offshore on shore facility up to	$50 million depending on threat and categories of facilities.

If the spill results from gross negligence or willful violation of safety regulations the liability of the vessel or facility will be unlimited. Unlimited liability is also imposed if the spiller fails to cooperate with Federal cleanup efforts. Failure to notify the Coast Guard of a spill may constitute a "failure to cooperate."

Each of the bills requires that evidence of financial responsibility to pay damages up to the limit of liability be furnished by vessels and facilities and that the financial responsibility be reflected by a Federal certificate. It should be noted that the liability limits are set at a level sufficient to pay for all damages except in the case of the catastrophic spill. Vessels and facilities may procure insurance or they may self-insure to meet financial responsibility requirements. In all spills, the designated spiller gets the first "portion" of liability, with the fund acting as a secondary compensation fund for all valid, yet uncompensated, claims.

The superfund bills presently before the Congress differ in the extent to which parallel state liability laws would be preempted by the comprehensive Federal law. Based on S. 1187, it appears that the Administration favors preemption of state laws on oil pollution liability, state compensation funds supported by a tax on oil, and state financial responsibility requirements. H.R. 6803 also reflects this design for state preemption. S. 2900 and S. 2083 do not preempt state oil pollution liability laws. None of the bills pending affect the states' authority to establish or fund pollution prevention or cleanup programs.

Under each of the bills (except S. 2900) there is a statute of limitations for submitting claims, though such a deadline does not affect the right to compensation for

damages that may persist longer than the statute of limitations. However, as in most injury cases, settlement on damage claims may be made immediately after the incident on the basis of expected future damages. The statute of limitations in H.R. 6803 for claim submission is 3 years from the discovery of the economic loss or 6 years from the pollution incident whichever is earlier.

Finally, of some interest to marine biologists are the provisions in the competing bills for damage assessment studies. The Administration bill, S. 1187, provides for damage assessment studies to be undertaken by the fund as a cost of claims adjustment for major oil spills. The S. 2900 fund may be used for damage assessment in any spill. Finally, S. 2083 provides for a $20,000,000 per fiscal year research program on the short and long term effects of oil pollution, to be conducted by NOAA.[52]

Conclusion

The superfund bills presently before Congress reflect an executive and legislative effort to find a legal solution to a problem brought on by our nation's dependence on oil as a fuel. The superfund proposals recognize the inadequacy of existing laws on pollution damages, and set out a legal framework that balances the interests of parties that transport and use oil, and those whose property, livelihood, and natural resources are damaged by oil.

FOOTNOTES

1. Polluting Incidents in and around U.S. Waters, Calendar Years 1976, 1977, CG-487 (available from U.S.C.G.).
2. See, e.g., Oppen v. Aetna Ins. Co., 485 F.2d 252 (9th Cir. 1973) (loss of use of pleasure boats not compensable); Burgess v. Tamano, 370 F.Supp. 247 (.S.D. Maine, 1973) (non-beachfront businesses, owners denied recovery for loss of profits).
3. One of the first oil pollution prohibitions of national application was the Refuse Act of 1899, 33 USC 407, 30 Stat. 1152. Before the Refuse Act, the New York Harbor Act of 1866 prohibited discharges in New York, Hampton Roads, and Baltimore harbors.
4. P.L. 89-753, 80 Stat.1253, 33 USC 431 et seq.
5. 9 Stat 635, 46 USC 181 et seq. This act limits the liability of a vessel to the value of the vessel after the incident plus the pending freight. Despite changes to the discharger's liability on the Federal level, the Limitation of Liability Act still applies to oil pollution damage claims. See generally, Sisson, Oil Pollution Law and the Limitation of Liability Act: A Murky Sea for Claimants against Vessels, 9 Journ. of Mar. Law and Commerce 285 (1978).
6. P.L. 91-611, 84 Stat. 1823, 33 USC 1161 (1970).
7. P.L. 92-500, 86 Stat. 862, 33 USC 1321 (1974 Supp.).
8. P.L. 95-217, ___ Stat.___, 33 U.S.C. 1321 (1978). The provisions concerning government recovery for damages to natural resources are poorly drafted and are virtually certain to be challenged.
9. P.L. 93-153, 87 Stat. 584, 43 USC 1653.
10. P.L. 19-627, 88 Stat. 2141, 33 USC 1517.
11. The TAPs fund, as of April 1, was built up to a level of approximately $5million. Since the marine leg of the TAPs system has been in operation, there have been only 4 spills of minor quantities of oil.
12. Methods and Procedures for Implementing a Uniform Law Providing Liability for Cleanup Costs and Damages Caused by Oil Spills from Ocean and Related Sources: A study by the Justice Department, printed pursuant to S. Res. 222 (94th Cong.,1st Sess.) (July 1975).
13. International Convention on Civil Liability for Oil Pollution Damage, 1969, 2] IEG 1501, 9 ILM 45.
14. International Convention for the Establishment of an International Fund for Compensation of Oil Pollution Damage, 1971, 21 IEG 1701, 11 ILM 284.
15. See H. Rept. 94-1489 Pt.1 (94th Cong., 2d Sess.)
16 13 Presidential Documents 408 (March 17, 1977).

17. 123 Cong. Rec. H. 9241 (Sept. 12, 1977) (95th Cong., 1st Sess.)
18. H.Rept. 95-340, Part 1,(95th COng., 1st Sess.)
19. 123 Cong. Rec. H9236 (Sept. 12, 1977) (95th Cong., 1st Sess.).
20. Ibid.
21. Ibid.
22. 124 Cong. Rec. S5396 (April 12, 1978) (95th Cong., 2d Sess.).
23. Section 311(b)(5) of the FWPCA requires that the discharger notify the Federal Government of the discharge or face up to a $10,000 fine and/or 1 year imprisonment. The "price" of notification is a civil penalty of up to $5000 for the discharge under § 311(b)(6). The public benefit from the notification provisions is the opportunity for rapid cleanup actions taken under § 311(c). These "self-enforcing" notification provisions of the FWPCA would remain unaffected by most of the superfund bills.
24. H.R. 6803, §106(b); S. 1187, § 106(b); S. 2083, § 9(c)-(d); S. 2900, §5(b)(2(B).
25. H.R. 6803, §107, S. 1187, § 107; S. 2083, §9 (e)-(f); S. 2900, §5(b)(3)(A) (procedures subject to regulations).
26. See, e.g., Oppen v. Aetna Ins. Co., 485 F.2d 252 (9th Cir. 1973)
27. See, e.g., Burgess v. M/V Tamano, 370 F.Supp. at 251.
28. Burgess v. M/V Tamano, 370 F.Supp. at 571-72; Union Oil Co., v. Oppen, 501 F.2d 558, 563 (9th Cir. 1974); Attorney General's study, supra note 12.
29. Burgess v. M/V Tamano, 370 F. Supp. at 250-51.
30. Union OIl Co. v. Oppen, 501 F. 2d at 570.
31. H.R. 6803, §103(a); S. 1187, §103(a); S. 2083, §7 (slightly different language); S. 2900 §3(a)(2)(F) (slightly different language).
32. H.R. 6803, §103(a)(1); S. 1187, §103(a)(1); S. 2083, §6; S. 2900, § 3(a)(1).
33. In addition to FWPCA cleanup costs, costs under §5 of the Intervention on the High Seas Act, and Section 18 of the Deepwater Port Act are charged to the spiller.
34. H.R. 6803, §103(a)(2); S. 1187, §103(a)(2); S. 2083, §7(1); S. 2900, §3(a)(2)(A).
35. H.R. 6803, §101(2); S. 1187, §101(y).
36. Mead and Sorenson, " The Economic Cost of the Santa Barbara Spill," paper delivered at the Santa Barbara Oil Spill Symposium (Dec. 16-18, 1970 Marine Science Inst., U of Cal Santa Barbara).
37. Insurance adjustors experienced in oil spill incidents recount cases where fishing vessels have intentionally steamed through an oil slick with fishing nets out. Adjustors have found that in some cases, the resultant claims for oil damaged nets must be discounted because the nets employed were long past their service life.
38. H.R. 6803, §103(a)(3); S. 1187, §103(a)(3); S. 2083, §(7(2); S. 2900, §3(a)(2)(C).

39. Oppen v. Aetna, Ins co., 485 F.2d 252, 260.
40. H.R. 6803, §103(a)(4); S. 1187, §103(a)(4); S. 2083, §7(3)(A); S. 2900, §3(a)(2)(C).
41. P.L. 92-265, 90 Stat. 331, 16 USC 1801.
42. Maine v. M/V Tamano, 357 F. Supp. 1097, 1099 ((S.C. Maine 1974).
43. H.R. 6803, §103(b)(3); S. 1187, §103(b)(3); S. 2083, §11; S. 2900, §3(a0(2)(C).
44. S. 2900 may be a model in this regard, though in most other aspects S.1187 and H.R. 6803 are better drafted.
45. Mead and Sorenson, supra.
46. H.R. 6803, §103(b)(5); S. 1187, § 103(a)(5); S. 2083, §7(3)(B); S. 2900, 3(A)(2)(D).
47. H.R. 6803, §103(a)(6); S. 1187, § 103(a)(6); S. 2083, §7(4); S. 2900, §3(a)(2)(E).
48. H.R. 6803, §103(a)(6);S. 1187, §103(a)(6). S. 2083 and S.2900 use the term "resulting from."
49. Mead and Sorenson, supra.
50. H.R. 6803, §103(a)(7); S. 1187, § 103(a)(7); S. 2083, §4(c)(4); S. 2900, §3(a)(2)(includes royalties, rentals and net profits share revenue.)
51. H.R. 6903, §104(b); S. 1187, §104(b); S. 2083, §6(b) S. 2900, §3(c)
52. S. 1187, §102(d); S. 2083, §4(c)(4); S. 2900, §5(a)(6) each permit the use of the find for assessing short term and long term effects of pollutants on natural resources.

FROM TORREY CANYON TO EKOFISK: A STUDY OF LEGISLATION BY CRISIS

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FROM TORREY CANYON TO EKOFISK: A STUDY OF LEGISLATION BY CRISIS

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The author describes the development of British law enacted to protect the marine environment from damage caused by oil. The legal framework intended to prevent both accidental and operational discharges of oil from offshore petroleum development is discussed, and compensation schemes for pollution damage are explained. Particular emphasis is given to factors which have shaped the present law and which may influence the future British legal regime of marine pollution control.

INTRODUCTION

On the morning of March 18, 1967, the *Torrey Canyon* ran aground off the Cornish coast and became "one of the major ship disasters in maritime history."[1]

The international community was awakened to oil pollution. No country felt the impact of this disaster more than did Britain. By 1971, several new acts responsive to the *Torrey Canyon* accident and its aftermath had been added to the British legal regime of oil pollution control.

In the decade that followed the *Torrey Canyon* grounding, the oil-rich North Sea continental shelf was explored and petroleum production begun; the first North Sea oil flowed from the Norwegian Ekofisk field in July, 1971. The British law controlling pollution from tankers had become fairly well developed. The research studies of scientists at Warren Spring Laboratory, a growing awareness that the law controlling land-based oil pollution was not necessarily applicable to offshore development, and accidents such as the *Sea Gem* disaster had contributed to the enactment of other law. However, gaps still existed.

Ten years after the *Torrey Canyon* spill, the blowout of a production well on the Bravo platform in the Ekofisk field transformed vaguely contemplated oil pollution from petroleum development into a shockingly real possibility. The Ekofisk blowout and the *Amoco Cadiz* grounding, uncomfortably near Jersey and Guernsey shores, is likely to

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[1] Liberian Board of Investigation Report on Stranding of *Torrey Canyon*, 6 *Int'l Legal Materials* 480 (1967).

hasten incorporation of the 1973 International Convention for the Prevention of Pollution from Ships and the 1976 International Convention on Civil Liability for Oil Pollution Damage into the British legal regime.

In the discussion that follows, the British law of oil pollution control will be described and forces which have helped shape the present regime will be analyzed. Based upon this discussion, the future pattern of legal developments will be predicted.

In the context of this discussion of British law, it should be remembered that prevention of oil pollution at sea may affect foreign nations and so become subject to international law. Some U.K. law is thus constrained, and occasionally expanded, by the necessity for fidelity to international law.

International customary law is considered to be part of British law, requiring no legislation to become effective.[2] On the other hand, treaty provisions frequently require enabling legislation to become incorporated into the national legal system. Enabling legislation must be consistent with treaty obligations to permit ratification without reservation, for a nation may not plead absence or inadequacy of its law in answer to a claim for breach of an international duty.[3] Several British laws relevant to prevention of oil pollution at sea are enabling legislation and have therefore been shaped by both international and national forces.

British law controls operational discharges of oil from vessels and offshore petroleum development, prevents accidental discharges from both sources, and compensates for oil pollution damage. Prior to the *Torrey Canyon* grounding, British legislation was primarily concerned with operational discharges from tankship ballasting and tank washing, although it included a few provisions regulating oil discharges from offshore petroleum development.

The Oil in Navigable Waters Act, 1955,[4] superseded earlier legislation[5] and incorporated the terms of an international convention[6] into national law.

The Continental Shelf Act, 1964,[7] extended functional British jurisdiction to the continental shelf so as to facilitate the recovery of its natural resources. This act regulated oil discharges from offshore installations and pipelines using the same standards that were being applied to vessels under the 1955 Act. The Continental Shelf Act thereby satisfied general obligations contracted pursuant

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2 Brownlie, *Principles of Public International Law* 45, 47 (2d. ed. 1973).

3 *Alabama Claims* (United States-Great Britain, 1872), Moore, *International Arbitrations* 496.

4 The Oil in Navigable Waters Act, 1955, 3 & 4 Eliz. 2, c. 25.

5 The Oil in Navigable Waters Act, 1922, 12 & 13 Geo. 5, c. 39.

6 International Convention for the Prevention of Pollution of the Sea by Oil, May 12, 1954, 12 U.S.T. 2989, T.I.A.S. No. 4900, 327 U.N.T.S. 3.

7 Continental Shelf Act, 1964, c. 29.

to the Geneva High Seas Convention[8] and the Geneva Continental Shelf Convention.[9] The Petroleum (Production) Regulations, 1966,[10] enacted under the authority of the Continental Shelf Act, applied land-based petroleum development procedures to offshore operations. This included provisions addressed to the prevention of oil pollution.

The *Torrey Canyon* disaster resulted in a 1969 conference concerning intervention with foreign vessels on the high seas to prevent coastal state oil pollution damage, and with civil liability for such damage. One resulting convention sets out conditions under which states parties may interfere with foreign shipping;[11] the second details liability should a convention state tanker damage another state.[12]

The Prevention of Oil Pollution Act, 1971,[13] contains provisions inspired by the *Torrey Canyon* spill and accidents involving the tankers *Allegro, Pacific Glory*, and *Panther*. The act was expanded beyond its original concern with improved operational discharge standards to include provisions authorizing interference with foreign vessels on the high seas to prevent damage from oil pollution.

The Merchant Shipping Act, 1971,[14] reflects the strict but limited liability provisions of the Civil Liability Convention opened for signature in 1969.

The Mineral Workings (Offshore Installations) Act, 1971,[15] is concerned with safety on offshore installations and was motivated by the collapse of the drilling rig *Sea Gem*.

Part I of the Merchant Shipping Act, 1974,[16] will expand the statutory provisions in British law for recovery for oil pollution

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[8] Convention on the High Seas, April 29, 1958, 13 U.S.T. 2312, T.I.A.S. No. 5200, 450 U.N.T.S. 82.

[9] Convention on the Continental Shelf, April 29, 1958, 15 U.S.T. 471, T.I.A.S. No. 5578, 499 U.N.T.S. 311.

[10] The Petroleum (Production) Regulations (1966 No. 898).

[11] International Convention Relating to Intervention on the High Seas in Cases of Oil Pollution Casualties, Nov. 29, 1969, 9 *Int'l Legal Materials* 25 (1970).

[12] International Convention on Civil Liability for Oil Pollution Damage, Nov. 29, 1969, 9 *Int'l Legal Materials* 45 (1970).

[13] Prevention of Oil Pollution Act, 1971, c. 60.

[14] Merchant Shipping (Oil Pollution) Act, 1971, c. 59.

[15] Mineral Workings (Offshore Installations) Act, 1971, c. 61.

[16] Merchant Shipping Act, 1974, c. 43.

damage when the convention which it is intended to implement comes into force.[17] Part II of the 1974 act sets design and construction standards for tankers, thereby permitting the acceptance of an amendment to the 1954 convention.[18]

The Petroleum and Submarine Pipelines Act, 1975,[19] includes a provision which recognizes that technological limitations may require a relaxation of oil discharge standards to a level realistically possible. It is not presently possible to completely separate oil from water resulting from offshore oil production. The 1975 Act therefore amends the Prevention of Oil Pollution Act, 1971, in order to permit controlled discharges of oil into the sea.

The present British law of oil pollution prevention has been greatly influenced by international treaties. Such agreements as the 1973 International Convention for the Prevention of Pollution from Ships[20] and the 1976 Convention on Civil Liability for Oil Pollution Damage Resulting from Exploration and Exploitation of Seabed Mineral Resources[21] are likely to shape future British law.

The development of British law is discussed below. To facilitate an understanding of the development of the law, control of pollution from vessels, prevention of pollution from offshore petroleum development, and civil liability for pollution damage are discussed separately.

THE U.K. LAW OF OIL POLLUTION CONTROL

Control of Operational Discharges from Vessels

The Prevention of Oil Pollution Act, 1971,[22] is the latest in a series of legislative instruments intended to control operational discharges of oil from vessels. A primary purpose of the act was to incorporate into British law amendments to the International Convention

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[17] International Fund for Compensation for Oil Pollution Damage, Dec. 18, 1971, 11 *Int'l Legal Materials* 248 (1972).

[18] Resolution to amend the International Convention for the Prevention of Pollution of the Sea by Oil, 1954, concerning Tank Arrangements and Limitation of Tank Size, 11 *Int'l Legal Materials* 267 (1974).

[19] Petroleum and Submarine Pipelines Act, 1975, c. 74.

[20] International Convention for the Prevention of Pollution from Ships, Jan. 15, 1974, 12 *Int'l Legal Materials* 1319 (1973).

[21] Convention on Civil Liability for Oil Pollution Damage Resulting from Exploration and Exploitation of Seabed Mineral Resources, May 1, 1977, Cmnd. 6791 (1977).

[22] The Prevention of Oil Pollution Act, 1971, consolidates the Oil in Navigable Waters Acts 1955 to 1971, plus section 5 of the Continental Shelf Act, 1964.

for the Prevention of Pollution of the Sea by Oil (hereinafter, the 1954 IMCO Convention).

The 1954 IMCO Convention resulted from concern by the British public at the increase of coastal marine pollution in the years following World War II. In 1952, the British government appointed the Faulkner Committee to investigate the problem.[23] The *Faulkner Report*, published in 1953, recommended the conclusion of a treaty to control the discharge of persistent oil by vessels.[24]

In 1954, a conference was convened under the auspices of the British government. The convention which resulted was subsequently deposited with IMCO, following the establishment of that organization.

The terms of the 1954 IMCO Convention are too well known to merit extended discussion. The essence of the convention is that intentional discharges of "oily mixtures" are prohibited near coastlines. These provisions were faithfully reflected in British legislation.[25] The convention has been criticized as ineffective for many reasons, most of which ignored the axiom that states do not relinquish sovereignty by treaty unless it is clearly in their self interest to do so, and that compromise characterizes such instruments.

There has been, however, at least one practical criticism. It came not from lawyers, but from scientists.

The 1954 IMCO Convention prohibited the discharge of certain oils within "prohibited areas" in a concentration greater than 100 parts of oil per million parts of mixture (ppm). Researchers at the U.K. Department of Industry's Warren Spring Laboratory were concerned that this formula did not accurately indicate potential environmental damage. A supertanker with a large capacity and high pumping rate could dilute large quantities of oil with seawater and thus introduce oil into a limited area at an alarming rate. Even smaller vessels could threaten oil pollution when they were stationary or slow steaming. Experimental evidence suggested that the amount of oil discharged, whether mixed with water or not, in relation to the distance travelled by a ship, was a better indicator of potential environmental damage than an oil-water dilution ratio.[26] The 1969 Amendments to the 1954 IMCO Convention, which change the permissible oil discharge criterion from an oil in effluent ratio to liters of oil discharged per mile, resulted from these findings. These amendments, although not accepted by enough states to come into force until 1978, were made applicable to British ships in 1973 by an order under the Prevention of Oil Pollution Act, 1971.

The future of British law intended to control operational discharges from vessels is linked to the fate of the Convention for the Prevention

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[23] Hansard, House of Commons, Official Report, Vol. 805, cols. 573-574 (Oct. 30, 1970).

[24] Committee on Prevention of Pollution of the Sea by Oil (Chairman: P. Faulkner, C.B.) (1953).

[25] The Oil in Navigable Waters Act, 1955, 3 & 4 Eliz., c. 25; The Oil in Navigable Waters Act, 1963, c. 28.

[26] Hansard, House of Commons, Official Report, Vol. 805, col. 576, Oct. 30, 1970).

of Pollution from Ships[27] (hereinafter, the 1973 IMCO Convention) and events at the Third United Nations Conference on the Law of the Sea (hereinafter, UNCLOS III). When the U.K. accepts the 1973 IMCO Convention or a treaty resulting from UNCLOS III, domestic law will have to be made consistent with British international obligations. However, even were Great Britain not bound by such instruments, the negotiations concerning their form and content may evidence emerging international customary law. This is particularly a possibility in the case of UNCLOS III. Evidence that governments believed certain state practices to be not inconsistent with international law would support appropriate British legislation. Moreover, the terms of a treaty not in force, or rules of international customary law, could be applied unilaterally to persons and vessels subject to British jurisdiction, as was done in the case of British vessels in regard to the 1969 Amendments to the 1954 IMCO Convention.

The 1973 IMCO Convention was one of two instruments[28] resulting from an International Conference on Marine Pollution, convened in London in 1973. Activities of a number of international organizations, including U.N. General Assembly Resolutions and a NATO conference on oil spills,[29] culminated in a 1969 IMCO Resolution declaring an intent to draft a comprehensive treaty for the control of vessel-source pollution.[30] The resulting 1973 IMCO Convention is not in force and has not yet been accepted by the U.K., although a White Paper containing draft clauses of the Merchant Shipping Bill which will incorporate the convention into British law has recently been published.[31] The convention was amended recently by a protocol[32] which effectively shelved Annex II, addressed to the regulation of chemical discharges. This action

[27] *See* footnote 20.

[28] The other was the Protocol Relating to Intervention on the High Seas in Cases of Marine Pollution by Substances Other than Oil, Nov. 2, 1973, 13 *Int'l Legal Materials* 605 (1974).

[29] *See* NATO, Committee on the Challenges of Modern Society, Coastal Water Pollution of the Sea by Oil Spills, No. 1, 1970.

[30] IMCO Assembly Resolution A. 176 (VI), Oct. 31, 1969.

[31] Department of Trade, Press Notice, Ref. 132, May 15, 1978, *referring to* the White Paper, *Action on Safety and Pollution at Sea: New Merchant Shipping Bill*, Cmnd. 7217 (May 15, 1978). The White Paper was intended to provide an opportunity for consultation and comment as it was thought unlikely that time to debate the Bill would be available in the present Session of Parliament. Some parts of the convention which can readily be implemented have been incorporated in a voluntary code prepared by the International Chamber of Shipping.

[32] TSPP/CONF/11, Feb. 16, 1978, Protocol of 1978 Relating to the International Convention for the Prevention of Pollution from Ships, 1973.

may hasten the coming into force of the convention by removing the objection that Annex II requirements were beyond the limits of present technology. Nevertheless, shipping interests remain concerned that the present state of the art will not permit compliance with the oil discharge provisions of the convention and argue that more sophisticated monitoring equipment and oil-water separators must precede acceptance.[33]

The 1973 IMCO Convention was intended to replace the 1954 IMCO Convention and its amendments with a far more comprehensive instrument which would regulate marine pollution caused by oil *and* other hazardous substances, whether resulting from operation *or* accident.[34] It will apply both to vessels and fixed or floating platforms, but it expressly excludes regulation of discharges resulting from seabed operations. The new convention is unusually technical, consisting in large part of five annexes setting forth detailed requirements for vessel construction and operation. Annex I is "Regulations for the Prevention of Pollution by Oil." Insofar as control of operational discharges of oil is concerned, the most significant addition is the redefinition of "oil" to include refined "white oils" which were not included in the 1954 IMCO Convention. Five "special areas" have been designated in which only discharges of "clean ballast" will be permitted, and a fifty-mile belt of coastal waters will remain an area into which no oil from tankers may be discharged.

UNCLOS III has now met seven times since 1973 in a continuing effort to conclude a comprehensive convention dealing with an extensive list of law of the sea issues. Following the Third Session, the chairman of each committee produced an Informal Single Negotiating Text which was intended to serve as a "procedural device" to facilitate agreement only, it being emphasized that the Text was not to be regarded as binding.[35] A Revised Single Negotiating Text incorporated changes resulting from the Fifth Session.[36] During the Sixth Session, a new Informal Composite Negotiating Text (ICNT) was produced as a vehicle for discussion at the Seventh Session, convened in Geneva on March 28, 1978.[37] Despite the caveat disclaiming the legal effect of the various texts, it is clear that some provisions enjoy such wide support that they may evidence emerging international customary law. For example, it is now commonplace for states to unilaterally declare that they exercise functional jurisdiction over extensive areas of coastal waters, a concept brought to maturity by UNCLOS III.

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[33] IMCO, MEPC VI/7. *See also*, OCIMF, *International Convention for the Prevention of Pollution from Ships, 1973: Position of the Oil Companies International Marine Forum* (October, 1974).

[34] The 1954 IMCO Convention applies only to operational discharges of crude oil.

[35] Committee III is concerned with marine pollution, scientific research and transfer of technology. *See*, Informal Single Negotiating Text, Part III, A/CONF.62/WP.8/Part III (May 6, 1975).

[36] Revised Single Negotiating Text, A/CONF.62/WP.10/Rev.1/Part III (May 10, 1976).

[37] Informal Composite Negotiating Text, A/CONF.62/WP.10 (July 15, 1977).

States may establish a territorial sea of up to twelve nautical miles. This extension from the present U.K. three-mile limit could facilitate increased control over vessel-source pollution by increasing the area over which, subject to the right of "innocent passage," the U.K. government would have sovereignty. But what is innocent passage?

The Geneva Convention on the Territorial Sea, to which the U.K. is a party, provides that "passage is innocent so long as it is not prejudicial to the peace, good order or security of the coastal State," but provides no further guidance.[38]

The ICNT clarifies the position of the coastal State by listing a number of acts which would be considered prejudicial to the coastal state, including "any act of wilful and serious pollution, contrary to the present Convention." This provision suggests that accidental pollution would be permissible, even if caused by gross negligence, and that the burden upon the coastal state of proving fault would be a heavy one indeed. Nevertheless, it does provide that wilful disregard of whatever standards are ultimately accepted would subject a vessel to coastal state jurisdiction.

The ICNT also provides that the coastal state could make laws relating to innocent passage through its territorial sea in relation to the conservation of coastal state living resources, and the preservation of the coastal state marine environment, including pollution prevention. However, such laws would have to conform to the proposed convention and could not affect vessel construction or manning standards unless authorized to do so by international law.

The ICNT proposes an Exclusive Economic Zone (EEZ) extending from the twelve-mile territorial sea up to 200 nautical miles from the baseline dividing the territorial sea and internal waters. This would be a zone *sui generis*, distinguishable from the high seas, wherein vessels would remain subject to the exclusive jurisdiction of the flag state. An extensive provision detailing flag state duties is clearly directed at the well-known problem of "flag of convenience" vessels.

States would be required to act through "the competent international organization"[39] or diplomatic conference to set standards for vessel-source pollution. Such international standards must be complemented by no less effective national regulations.

Coastal states would be authorized to establish standards in their territorial seas "in exercise of their sovereignty," subject only to the right of innocent passage. Coastal states could establish laws to enforce international standards within their EEZs. However, where

1. international standards are inadequate to meet "special circumstances," and
2. the coastal state reasonably believes that a specific part of its EEZ should be designated a special area pursuant to

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[38] Article 4. Convention on the Territorial Sea and Contiguous Zone, April 29, 1958, 15 U.S.T. 1606, T.I.A.S. No. 5639, 516 U.N.T.S. 205.

[39] This is likely to be IMCO.

enumerated criteria,

the coastal state could enact legislation consistent with standards promulgated by "the competent international organization."

Finally, UNCLOS III may provide for more effective enforcement of standards set for the control of discharges from vessels. In essence, the relevant ICNT Articles provide for limited "port state" jurisdiction and enforcement to complement that of the flag state. Port state jurisdiction would authorize coastal state investigation and, under certain circumstances, prosecution of foreign flag vessels which have violated internationally-agreed discharge standards and are located within the coastal state's port.[40]

This brief summary of relevant UNCLOS III provisions suggests a trend to increased coastal state jurisdiction over activities in an extended area from its shores. An increased recognition of a right to act unilaterally, within broad limits, may provide the U.K. with an opportunity to implement a more effective scheme of oil pollution control than has hitherto been possible.

Prevention of Accidental Discharges from Vessels

"Shipping Casualties" is a discrete cluster of provisions so identified in the Prevention of Oil Pollution Act, 1971. The Act originally did not contemplate a "Shipping Casualties" section, nor, for that matter, were any such powers provided for by statute. The *Torrey Canyon* grounding on March 18, 1967, had resulted in the International Convention Relating to Intervention on the High Seas in Cases of Oil Pollution Casualties which defined the circumstances under which states parties thereto could interfere with foreign vessels on the high seas to protect their territory from oil pollution damage. The U.K. government had not thought it necessary to enact enabling legislation, reasoning that a right of intervention already existed under international customary law.[41] Two accidents which occurred during Parliamentary debate of a bill antecedent to the Prevention of Oil Pollution Act caused the British government to reconsider this position and to conclude that legislation clarifying the right of interference to prevent coastal oil pollution was desirable.

On October 23, 1970, the Liberian-registered tankers *Allegro* and *Pacific Glory* collided outside the U.K. territorial sea. The *Pacific Glory* caught fire, was abandoned with loss of life, and ultimately settled on a shingle bank four miles off the coast. The British government and the salvage company cooperated in freeing the

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[40] Port state jurisdiction provides an alternative to interference with foreign shipping on the high seas by coastal states. *See* International Law Association (British Branch), "The Concept of Port Jurisdiction," a paper presented to the New Delhi Conference, 1964.

[41] Hansard, House of Lords, Official Report, Vol. 315, col. 50, Feb. 9, 1971.

vessel, and little apparent damage occurred. The government remained publicly unshaken in its belief that no new powers were needed to cope with such incidents. It was thought, however, that an incident involving a foreign vessel *within* the U.K. territorial sea could raise a question of the right to interfere with innocent passage. It was decided to clarify this issue by enacting legislation to set out the government's right to act in the event of a vessel casualty within U.K. waters.[42]

On March 30, 1971, the tankship *Panther* grounded just outside U.K. territorial waters. As in the *Pacific Glory* case, she was quickly attended to, but, in this instance, difficulties were encountered in the attempts to free the vessel and relations between the government and the salvor became strained. The first salvor to reach the scene refused offers from competitive tugs despite the fact that his own tugs could not free the stricken oil carrier. Repeated government efforts were necessary to expedite the transfer of oil to smaller vessels so that the *Panther* could be freed. These difficulties contributed to an expansion of the "Shipping Casualties" amendment to include powers to intervene with accidents to vessels on the high seas.[43]

The Secretary of State may exercise the powers conferred upon him under the "Shipping Casualties" Section when:

1. an accident has occurred to or in a ship; and
2. in the opinion of the Secretary of State, oil from the ship will or may cause pollution on a large scale in the United Kingdom or in the waters in or adjacent to the United Kingdom up to the seaward limits of territorial waters; and
3. in the opinion of the Secretary of State, the use of of the powers conferred by this section is urgently needed.

These provisions are similar to those specified in the 1969 IMCO Intervention Convention.

In the above circumstances, the Secretary of State is empowered to give directions to the master, owner, or any person, salvor, or salvors agent in possession of the ship in order to prevent oil pollution. If, in the opinion of the Secretary of State, action is necessary, he may:

1. do anything which he could have directed be done, *e.g.*, engage relief tankers to receive oil;
2. sink or destroy the ship;
3. assume control of the ship.

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[42] The "Shipping Casualties" Section was introduced as an amendment to the Oil in Navigable Waters Bill in the House of Lords on February 9, 1971. After debate, it was accepted, and the amended Bill was sent to the House of Commons.

[43] The government introduced an amendment in the House of Commons to extend the "Shipping Casualties" Section to shipping accidents which occurred outside British waters. Hansard, House of Commons, Official Report, Vol. 815, col. 638, April 7, 1971.

An order made pursuant to the Prevention of Oil Pollution Act provides that the "Shipping Casualties" Section of the Act applies to foreign-registered vessels outside U.K. waters.[44]

British law thus clearly authorizes the government to deal with situations like the *Torrey Canyon, Argo Merchant,* or *Amoco Cadiz*. There is, however, much force to arguments that because the right of intervention only arises after an accident, and then only in regard to the prevention of massive oil pollution, it is of limited utility. Although IMCO is to publish "Guidelines for Possible Intervention Under the 1969 Intervention Convention,"[45] this is unlikely to authorize action prior to a vessel casualty. It is suggested that such authority awaits the emergence of international customary law permitting extended coastal state jurisdiction for the purpose of pollution prevention. An UNCLOS III treaty would also be likely to confer this right, but it appears to the writer more likely that customary law in this respect will develop before an UNCLOS III treaty comes into force.

Part II of the Merchant Shipping Act, 1974, is enabling legislation which permitted U.K. ratification of the 1971 "Tanks" Amendment to the 1954 IMCO Convention.[46] The essence of that amendment was to regulate the size and arrangement of cargo tanks in certain new and existing oil tankers for the purpose of minimizing oil discharge in the event of tank rupture. As the amendment is not yet in force, the act presently cannot be applied to foreign vessels.

In summary, the scheme of regulation is based on a power to require that British oil tankers qualify for a "tanker construction certificate" or a "tanker exemption certificate" before such vessels may engage in trade. Such certificates will be issued to vessels which have satisfied criteria to be specified in "oil tanker construction rules" on the basis of reports by surveyors. When the entire Act comes into force, the British government will be authorized to detain any uncertificated vessel.

The 1971 "Tanks Amendment" and, consequently, Part II of the Merchant Shipping Act, 1974, have been overtaken by events, *viz.*, the *Argo Merchant* grounding off the U.S. East Coast and the subsequent reaction of both the legislative and executive branches of the U.S. government.

In his message to Congress on March 18, 1977, President Carter called for early ratification of the 1973 IMCO Convention, and further stated that the U.S. would seek a reform of ship constuct-

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[44] The Oil in Navigable Waters (Shipping Casualties) Order (1971 No. 1736), in force Nov. 22, 1971. The Secretary of State has not had occasion to exercise his powers under the "Shipping Casualties" Section.

[45] *Annual Report of the Inter-Governmental Maritime Consultative Organization, 1976-1977*, p. 14, para. 57. The Legal Committee has deferred work on a possible convention on wreck removal and related issues, an instrument which may address itself to the question of drifting vessels which threaten coastlines, other vessels, or offshore installations. *Ibid.*, p. 17, para. 70.

[46] *See* footnote 18.

ion standards to include, *inter alia,* double bottoms on all new tankers and segregated ballast on all tankers.[47] Two months later, in an address to the IMCO Council, U.S. Secretary of Transportation Brock Adams noted U.S. concern following "no less than fifteen incidents involving tankers in or near U.S. waters within a three and a half month period," and pointedly informed delegates that the U.S. was moving rapidly to develop legislation and subordinate rules which would implement the President's recommendations--unilaterally, in the absence of international agreement.[48]

U.S. efforts are reflected in the Protocol of 1978 Relating to the International Convention for the Prevention of Pollution from Ships, 1973.[49] The 1978 Protocol amends the 1973 Convention in pertinent part by reducing from 70,000 tons to 20,000 tons the new tankers which will be required to be constructed with segregated ballast tanks. However, the U.S. proposal for double bottoms on all new tankers was not accepted, the Protocol instead reflecting a compromise in the provision that segregated ballast tanks be located so as to afford protection in the event of grounding or collision. The sudden interest by the U.S. in the 1973 IMCO Convention will certainly hasten its coming into force and its consequent replacement of the 1954 IMCO Convention. Maritime casualties off the U.S. Atlantic Coast therefore appear likely to shape British law intended to prevent vessel source pollution.

Control of Operational Discharges from Offshore Exploration and Production: the Prevention of Oil Pollution Act, 1971, Section 3

Section 3 of this act provides that the discharge of oil or an oily mixture into any part of the sea, from a pipeline or "as the result of any operation for the exploration of the sea-bed and subsoil or the exploitation of their natural resources" constitutes an offense for which the owner or operator shall be liable. The plain meaning of Section 3 is that the discharge of *any* oil from offshore operations is illegal. This was workable so long as petroleum development operations were confined to exploration. However, some oil is always present in water associated with petroleum production and present technology does not permit complete separation of oil from water. It was decided, therefore, to permit controlled discharges of oil into the sea from production operations.

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47 "The Fight Against Oil Pollution: President Carter's Message to Congress," Official Text provided by the American Embassy in London, March 21, 1977.

48 XXXVIII Session of the Council of the Intergovernmental Maritime Consultative Organization, "Statement by the Honorable Brock Adams, Secretary of Transportation, United States of America, May 23, 1977."

49 *See* footnote 32.

The Prevention of Oil Pollution Act was amended by the Petroleum and Submarine Pipelines Act, 1975,[50] to permit the Secretary of State to make exemptions to the absolute prohibition of oily discharges. Department of Energy policy is that operators use the "best practicable" means to minimize oil in discharged effluent.[51] Operators must "normally maintain the oil content of any discharge below an average of 40 - 50 ppm, and below 100 ppm 96 percent of the time," depending upon the discharge volume.[52] It is noteworthy that the wide discretion to set discharge standards is vested in the Department of Energy, rather than the Department of Environment or some other department. Of course, it is true that Energy has unequalled expertise upon which to base its discretion, but that department may be subject to a very real conflict of interest between its primary task of energy production and an incidental duty of environmental protection. This point was raised in the House of Lords, but was summarily dismissed by the government.[53]

The U.K. at present may set standards for operational discharges from offshore petroleum development unfettered by specific requirements imposed by international law. It is possible that this freedom may be curtailed, however, by a most unlikely-appearing regional agreement, the Convention for the Prevention of Marine Pollution from Land-based Sources (hereinafter, the Paris Convention).[54] The "pollution from land-based sources" to which the Paris Convention applies includes that affecting "the maritime area," as well as that from

> "man-made structures placed under the jurisdiction of a Contracting Party within the limits of the area to which the present Convention applies."

If this provision is determined to apply to drilling and production installations, the U.K. may well be bound by oil-water discharge standards enacted pursuant to this authority.

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50 *See* footnote 19.

51 U.K. Department of the Environment, Central Unit on Environmental Pollution, *The Separation of Oil from Water for North Sea Oil Operations*, Pollution Paper No. 6 (1976), p. 16.

52 U.K. Department of Energy, *Development of the Oil and Gas Resources of the United Kingdom, 1977*, p. 16. "Large platforms capable of discharges in excess of 100,000 barrels per day are required to maintain an average oil content in their discharge of less than 40 ppm. Smaller platforms capable of discharges of between 1,000 and 100,000 barrels per day will be required to maintain oil content below 50 ppm average."

53 Hansard, House of Lords, Official Report, Vol. 384, cols. 994-995, June 27, 1977.

54 Convention for the Prevention of Marine Pollution from Land-based Sources, 13 *Int'l Legal Materials* 352 (1974).

Prevention of Accidental Discharges
from Offshore Exploration and Production

The Continental Shelf Act, 1964, enabled ratification of the Geneva Conventions on the Continental Shelf and on the High Seas, thereby facilitating development of newly discovered and suspected North Sea hydrocarbon resources.[55] The essence of the act is the extension of British functional sovereignty to the continental shelf. The act thereby provides a basis for legislation more directly concerned with the prevention of oil pollution from offshore petroleum development. Several other acts are expressly extended to the continental shelf, including Part II of the Coast Protection Act, providing for control of installation siting, and the Submarine Telegraph Act, relevant here because it was expanded to include sumbarine pipelines in its provisions dealing with punishment for cable damage and compensation for gear sacrificed to avoid such damage.

The Mineral Workings (Offshore Installations) Act, 1971,[56] is essentially a grant of authority to the Secretary of State to enact safety regulations governing U.K. offshore installations, and to impose responsibility for safety upon "installation managers." The act is drafted in general terms; great reliance is placed upon subordinate regulations to implement details thought necessary for safe offshore operations.[57]

The impetus for the Mineral Workings Act was provided by the collapse of the drilling rig *Sea Gem*. An inquiry into the disaster resulted in a report which included several recommendations. The Mineral Workings Act incorporated nearly all of these,

> "particularly those about construction and operating techniques, facilities and codes of construction which vary enormously from one type to another, discipline and the chain of command."[58]

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55 *See* footnotes 7, 8, and 9.

56 *See* footnote 15.

57 The Mineral Workings Act was intended to supplement the safety provisions inserted into licenses which formerly were the sole means of safety regulation. A statutory scheme of safety regulation was thought necessary because appropriate penalties for different violations could be imposed, because standards could more easily be made uniform, and because an overall safety scheme could be presented more clearly. Hansard, House of Lords, Official Report, Vol. 315, cols. 742-743, Feb. 18, 1971.

58 Hansard, House of Commons, Official Report, Vol. 816, col. 651, April 28, 1971. *See also*, Report of the Inquiry into the Causes of the Accident to the Drilling Rig *Sea Gem* 1966-67, Cmnd. 3409 (October, 1967).

Although compliance with the standards and procedures subsequently imposed by the act probably would not have prevented the structural failure which was the immediate cause of the disaster, the new requirements concerning organization and management implemented existing techniques and may well have mitigated loss of life had they been employed. It is pertinent to observe, in this regard, that the Norwegian Commission of Inquiry appointed to investigate the Ekofisk blowout found that,

> "the underlying cause of the accident was that the organizational and administrative systems were on this occasion inadequate to assure safe operations."[59]

One might speculate as to whether British law would have been more effective than Norwegian law in preventing the Ekofisk blowout. In the writer's view, it would not have been. The U.K. and Norway have sailed on different courses to the same destination. Early Norwegian law was characterized by great detail in statutory instruments; conversely, the Mineral Workings Act is but general authority for subordinate regulations which are gradually being promulgated. Subsequent Norwegian decrees have become less detailed and subordinate instruments have been issued pursuant to their authority. Both states have enacted regulations concerned with training, organization and administration--some specifically addressed to pollution prevention.[60] It is likely that this emphasis will continue, in view of the Commission's additional findings that "the accident to a large degree was due to human errors," and that although "certain technical weaknesses were present," they were "only of peripheral significance for the course of events."[61]

There has been some movement toward unification of safety and construction standards for offshore installations located on the continental shelves of the various North Sea states, but progress has been slow. A Conference on Safety and Pollution Safeguards in the Development of North-West European Offshore Mineral Resources which met in 1973 concluded that a coordinated approach to the safety of installations in the North Sea was desirable.[62] The work of

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[59] Report from the Commission of Inquiry appointed by the Royal Decree of 26 April 1977, Uncontrolled Blowout on Bravo (April 22, 1977).

[60] Schedule 2 of the Offshore Installations (Operational Safety, Health and Welfare) Regulations (1976 No. 1019) and Section 4 of the Offshore Installations (Emergency Procedures) Regulations (1976 No. 1542) respectively require written drilling production procedures and the maintenance of an emergency procedure manual. The emergency manual must specify action to be taken in several events, including a blowout or any discharge of oil or gas.

[61] Report from the Commission of Inquiry appointed by the Royal Decree of 26 April 1977, *op. cit.* in footnote 59.

[62] SPC (73) 18 Final, para. 1. Unpublished proceedings courtesy of the Norwegian Petroleum Directorate.

the Conference has been continued by subcommittees, and is expected to produce, if not a regional convention on safety standards, at least a code of recommended practice.[63]

Uniform standards are less important for fixed installations than they are for mobile units which may become subject to varying requirements as they move among jurisdictions. However, uniformity does tend to simplify procedures, and may, in this regard, promote pollution prevention. Moreover, the U.K. has two agreements with Norway involving joint administration of offshore installations, and uniform standards in these circumstances would aid enforcement of pollution prevention law.

The Ekofisk Agreement[64] concerns the submarine oil pipeline from the Ekofisk Field in the Norwegian sector to Teeside in the U.K. Norwegian standards are applied to the pipeline over its entire length; British standards are applicable as well to that section which lies within the U.K. sector. All pipelines, including those which feed into the main trunk line, "shall to the extent possible be subject to a uniform safety standard." A Commission consisting of three representatives from each state is responsible for administering the Agreement, and provision is made for the resolution of disputes through arbitration.

The Frigg Agreement[65] concerns development of a shared gas deposit bisected by the U.K.-Norwegian dividing line, as well as transmission of recovered gas to the United Kingdom. The most important provision of the Frigg Agreement which relates to pollution control provides that

> "the two Governments undertake to make every endeavour jointly and severally, after consultations, to ensure that the exploitation of Frigg Gas or the operation of any installation or pipeline involved in that exploitation shall not cause pollution of the marine environment or damage by pollution to the coast-line, shore facilities or amenities, or vessels or fishing gear of any country."

The Agreement contains a number of provisions which promote pollution prevention by requiring some effort toward uniform construction and safety standards, but most of the legal provisions relevant to pollution control are contained in the national legislation of the two states. The Frigg Agreement is similar to the Ekofisk Agreement in that provision is made for a Commission which is responsible for implementation, and an arbitral tribunal may be constituted at the request of either government to settle disputes not resolved by the Commission.

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63 *See*, Birnie, "Did Failures in the North Sea Legal Regime Contribute to the Ekofisk Blow-out?" *Oceanology International* 78, pp 3-9 (1978).

64 13 *Int'l Legal Materials* 26 (1974).

65 Cmnd. 6491 (1976).

Part III of the Petroleum and Submarine Pipelines Act, 1975,[66] authorizes government control of the construction, use, and routing of submarine pipelines on the U.K. continental shelf. The first regulation relevant to pollution control has recently been issued under the authority of the act. It concerns the powers and duties of inspectors.[67] The act itself is also of interest because it is carefully drafted to apply without reservation only to pipelines with a terminus at a point within U.K. jurisdiction. A pipeline which merely traverses the U.K. continental shelf may be regulated only the the extent "consistent with the jurisdiction which belongs to the United Kingdom under international law." This is consistent with the *Geneva Conventions on the Continental Shelf* and the *High Seas*, to which the U.K. is a party, and probably reflects international customary law as well.

The Petroleum (Production) Regulations, 1976,[68] contain the licensing system that is the primary means of controlling the exploration and exploitation of the U.K. continental shelf. They consist of a short body of 12 sections, plus appended schedules containing model clauses for various types of licenses. A number of model clauses included in both exploration and production licenses are of particular relevance to the control of marine pollution from offshore operations. Generally, the holder of a production license must

> "use methods and practice customarily used in good oilfield practice for confining the petroleum obtained from the licensed area in tanks, gasholders, pipes, pipelines or other receptacles constructed for that purpose."

"Good oilfield practice" is a standard that was established by many states in an attempt to control offshore activity for which there was not precedent in their law. The approach offers the advantage of flexibility in that initial standards may be predicated upon experience accumulated from exploration and production on land, but then can be modified as offshore technology and practice develop. On the other hand, it may be asked whether the offshore petroleum industry should participate to such an extent in setting its own standards.[69] The "good oilfield practice" criterion of performance is generally being replaced by legislation based upon what experience has shown is possible or "practicable." Where

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[66] *See* footnote 19.

[67] The Submarine Pipelines (Inspectors etc.) Regulations (1977 NO. 835).

[68] (1976 No. 1129), issued pursuant to the authority of the Petroleum (Production) Act, 1934 and the Continental Shelf Act, 1964. The 1976 Regulations consolidate earlier law.

[69] *See*, Code of Safe Practice for Drilling and Production in Marine Areas compiled by the Institute of Petroleum.

experience or technology is insufficient to support concrete standards or procedures, "good oilfield practice" or "best practicable" is still used, as is the case with permissible operational discharges from production installations. Moreover, the industry standard is still used to set a general "floor" on activities. For example, the obligation to work in accordance with good oilfield practice is specified by model clauses which require the licensee to take all steps practicable in order to prevent the escape of petroleum.

Compensation for Oil Pollution Damage

Compensation under British common law would be characterized by a number of uncertainties, the most important of which concerns the standard of care required of the defendant. Generally, liability is predicated upon "fault;" that is, the defendant must be found to have acted negligently in order for the plaintiff to recover. However, some socially desirable activities may be dangerous even when conducted with a high degree of care. Blasting is the classic example. In such cases, there is a trend toward shifting the risk of loss on the one who can best bear it; for example, by passing on the increased cost of doing business to the public. Under a "strict liability" system, a plaintiff need only prove that the defendant caused the damage complained of in order to recover--unless the defendant is relieved from liability by an unforeseeable, independent intervening event, such as an "act of God."

The English case of *Rylands v. Fletcher*[70] held that a defendant will be strictly liable

> "when he damages another by a thing or activity unduly dangerous and inappropriate to the place where it is maintained, in the light of the character of that place and its surroundings."[71]

It is an open question whether English courts would find the carriage of oil in bulk or offshore petroleum development activities to be subject to a strict liability standard. Moreover, Scottish law differs from its English counterpart in that it holds those engaged in abnormally dangerous activities to an unusually high standard of care, rather than applying strict liability.

A further question under British law is the extent to which loss must be immediately consequential upon injury to the plaintiff's person or property. This is of particular importance in regard to claims by fishermen for damage to fish not reduced to possession. The fishermen may clearly have suffered an economic loss, yet it is the loss of opportunity rather than the loss of property. There has been some discussion of establishing a fund to compensate such

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[70] L.R.3H.L330 (1868).

[71] Prosser, *Law of Torts* 508 (4th ed. 1971). *Cf.* Rogers, *Environmental Law* 159 (1st ed. 1977), who disagrees with Dean Prosser's belief that strict liability is confined to things or activities which are extraordinary, exceptional, or abnormal.

injury, but this has not yet occurred.

Some of the uncertainty of the common law highlighted above has been reduced by legislation. However, many aspects of civil liability remain uncodified and therefore governed by the common law or industry compensation schemes.

Two Merchant Shipping Acts are concerned with compensation for oil pollution damage. The Merchant Shipping (Oil Pollution) Act, 1971,[72] incorporates into British law provisions of the International Convention on Civil Liability for Oil Pollution Damage[73] (hereinafter, the 1969 IMCO Convention), a companion to the 1969 IMCO Intervention Convention, and like it, a result of the *Torrey Canyon* accident.

The *Torrey Canyon* had raised three main problems related to liability for damage caused by the discharge of oil from vessels:

1. Should liability be based on fault or some other standard?
2. Should there be limits to liability?
3. Should there be a specified forum state?

The answers to these questions constitute the essence of the British act.

The owner of a crude oil carrier is strictly liable for oil pollution damage and clean up costs within the U.K., including the territorial sea. Liability is subject to enumerated exceptions, and the owner may exonerate himself in whole or in part if the victim is found to have been contributorily negligent. The scope of liability is also limited by the language of the act which excludes most non-tankships as well as all discharges of light oils and refined petroleum products. The issue of compensation for damage to "non-property" interests is left to the courts to decide.

The owner's strict liability is balanced by a provision that it be limited, and exempts the servants and agents of the owner as well as any person performing salvage operations from any liability whatsoever. The act thus becomes the exclusive means of recovery in U.K. law. An owner may limit his liability to 9,054,122.94 British pounds.[74]

British courts have jurisdiction only over claims for damage done in the U.K. or its territorial waters. This reduces opportunities for "forum shopping," a practice by which those who can afford to do so may select the country offering the most advantage prospects of recovery.

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72 *See* footnote 13.

73 *See* footnote 12.

74 "The sterling equivalents and official sterling values have been calculated by reference to the special drawing right ('SDR') value of a gold franc converted into sterling at current market rates: the SDR is based on a basket of 16 major world currencies." The Merchant Shipping (Sterling Equivalents) (Various Enactments) Order (1978 No. 54).

Part I of the Merchant Shipping Act, 1974,[75] enabled ratification of the International Compensation Fund which was established to complement the Civil Liability Convention.[76] The 1974 act is intended to establish a fund constituted from a tax on oil imports for use in certain cases of damage not within the 1971 act, as well as to shift some of the liability for oil pollution damage from the ship owner to the cargo owner. These provisions reflect the disagreement among delegates to the 1969 Brussels Conference which concluded the 1969 Civil Liability Convention. That dispute turned in part on whether the cargo owner as well as the ship owner should be held liable under the proposed convention. It was resolved by providing that although the 1969 treaty would provide only for shipowner liability, a further convention should provide for the cargo owner to be liable in certain instances and for an increased liability limit. These provisions are reflected in the 1974 act which will provide compensation for victims of oil pollution damage in the U.K. who were unable to obtain full compensation under the 1971 act because:

1. an exception barred recovery,
2. the person liable cannot meet his obligations, or
3. the damage exceeds the liability limits of the 1971 act.

Certain exceptions to the protection offered to oil pollution victims remain, however, and it is clear that the 1974 act is far from an insurance scheme. Moreover, although the 1971 act and 1974 act combined have a liability ceiling of approximately 20 million pounds, this sum is believed by some observers to be inadequate to compensate for a major tanker spill near the British coast.

Compensation for vessel-caused oil pollution damage may also be effected by industry agreement. TOVALOP is an acronym for Tanker Owners Voluntary Agreement concerning Liability for Oil Pollution.[77] TOVALOP was formed by tanker owners after the *Torrey Canyon* incident as an interim measure of protection pending the coming into force of the 1969 IMCO Civil Liability Convention. Although the convention is now in force, TOVALOP continues to be effective and is relevant to cases of oil pollution caused by a tanker registered in a state not bound by the convention.

Tanker owners bound by TOVALOP are presumed to be negligent if one of their tankers discharges or threatens to discharge persistent oil which damages or may damage the coastline of any state. Liability is limited to $10 million per incident. Like the 1969 IMCO Civil Liability Convention, TOVALOP is limited to underwriting the cost of coastal cleanup. However, TOVALOP is even more restrictive than the convention both in regard to liability limits and in use of presumed negligence rather than strict liability as a standard for recovery. Presumed negligence reverses the usual burden of proof; unless the defendant can prove that he was not at fault,

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[75] *See* footnote 16.

[76] *See* footnote 17.

[77] The original agreement is reproduced at 8 *Int'l Legal Materials* 501 (1969). It has since been amended.

the plaintiff will recover. Conversely, under strict liability, the plaintiff need only prove that the defendant caused the damage in order to recover, unless liability is barred by a few exceptions. Thus, in one case, proof of care is a defense, in the other, it is not.

TOVALOP's narrow scope has caused some observers to note that the apparent *raison d'etre* of the agreement was to pre-empt more comprehensive regulation by national governments. Nevertheless, it should be noted that TOVALOP has made thousands of awards, including payments of $800,000 for the *Allegro-Pacific Glory* spill[78] and $1.1 million for clean up costs following the *Argo Merchant* grounding.[79]

The Contract Regarding an Interim Supplement to Tanker Liability for Oil Pollution (CRISTAL) provides a fund to augment the resources of the Civil Liability Convention and TOVALOP.[80] CRISTAL, in force since 1971, is an agreement among oil cargo owners intended to increase the money available for oil pollution compensation until the 1971 Fund Convention comes into force.

Like the Fund Convention, CRISTAL seeks to spread the risk of liability for oil pollution damage by providing that in certain instances the owner of oil cargo carried by sea may become liable for up to $30 million. This sum is subject to a "clean up deduction," which is intended to ensure that CRISTAL does not pay claims for which TOVALOP is liable.

The future of CRISTAL is unclear. On the one hand, CRISTAL may be superseded by national legislation which establishes compensation funds. Although Great Britain appears to be some years away from such a scheme, action by the United States and other major oil-importing states may mean that the Fund Convention never obtains the necessary ratifications to come into force, thus ensuring CRISTAL's longevity.

<u>Compensation for damage caused by discharges from offshore petroleum development: the 1976 Civil Liability Convention.</u>[81] Legislation being prepared to implement the 1976 Convention on Civil Liability for Oil Pollution Damage Resulting from Exploration and Exploitation of Seabed Mineral Resources (hereinafter, the 1976 Civil Liability Convention) will alter existing means of recovery under the common law and the industry compensation scheme, OPOL (discussed below). The most significant change will be a statutory strict liability standard imposed upon the operator of an offshore installation or pipeline. On the other hand, there will be a limit to the amount for which the operator may be held liable. Like the other instruments dealing with compensation, the convention does

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78 Shell Briefing Service, "Oil Spills Offshore--Compensation and Remedies," p. 2 (January, 1976).

79 8 *Environment Reporter* 1117 (1977).

80 The original contract is reproduced in 10 *Int'l Legal Materials* 137 (1971). It has since been amended.

81 *See* footnote 21. *See also*, Fitzmaurice, "Liability for North Sea Oil Pollution," 2 *Marine Policy* 105 (1978).

not set out with precision what sorts of damage may be covered by its terms, thus leaving national law unclarified in that respect.

Examination of the 1976 Civil Liability Convention *travaux preparatoires* indicates that the treaty provisions, and hence the terms of implementing legislation, reflect a compromise between the Norwegian and British delegations. It is not surprising that a compromise was necessary, for Norway and the U.K. have taken different approaches to the development of their North Sea petroleum resources. Norway has a sound economy, a small population, and abundant hydroelectric power by which most of its energy needs are satisfied. The Norwegian government therefore has emphasized orderly development of hydrocarbon resources from their continental shelf. Great Britain, on the other hand, needed immediate oil production to fuel her sputtering industrial machine and to help rectify serious balance of payments problems. It has been the British government's policy, therefore, to urge actions which would expedite the development of North Sea oil and gas.

The crux of the Norwegian-British disagreement was the extent to which the operator of an offshore installation or pipeline ought to be held liable. This, in turn, depended to some extent on views concerning possible and probable oil pollution damage resulting from a blowout or pipeline rupture, as well as the capacity of the insurance market to underwrite the risk. At a conference held in London in October, 1975, the Norwegian estimate of possible damage from a blowout was $60 million; the Association of Norwegian Insurance Companies indicated that $40 million was insurable.[82] The British estimate of possible pollution damage was that it would be under $25 million in any event, a figure also thought to describe the maximum insurance available per operator. The fundamental nature of the differences dividing the two delegations was indicated in a Norwegian proposal conceding only that liability be limited to $50 million, and that each state party retain the right to impose higher or unlimited liability for operators within its own jurisdiction. Compulsory insurance would be required up to a limit of $30 million. As a final gesture of compromise, the Norwegian delegation suggested that liability be limited to $35 million and compulsory insurance to $25 million for five years, after which the ceiling would be raised to $45 million potential liability and $40 million required insurance. This formula was unacceptable to the British delegation which objected to the high liability and insurance, as well as to the requirement of self-insured excess, which it was thought would prevent any but the largest companies from expanding their operations. Despite these and other British objections, the 1976 Civil Liability Convention bears a remarkable resemblance to the Norwegian proposal.

The operator of an offshore installation may limit his liability under the convention for each installation and each incident to 30 million Special Drawing Rights until 1982, at which time the ceiling will rise to 40 million SDRs.[83] The provision permitting deviation

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82 Unpublished October, 1975, Conference papers courtesy of the Norwegian Department of Environment.

83 SDRs are becoming increasingly popular as units of account in international conventions. The gold franc had provided satsifactory

from these limits suggested by the Norwegian delegation has been retained, although it is unlikely that the imminent British legislation will incorporate this option.

Companies bound by the Offshore Pollution Liability Agreement (OPOL) accept strict liability up to $25 million per incident for pollution damage and for the cost of remedial measures when injury has resulted from an escape or discharge of oil from offshore exploration or production operations.

OPOL is a direct result of the 1973 conference of nine Northwest European states which discussed problems associated with the development of offshore mineral resources. It was decided to work toward a convention concerned with safety in offshore mineral development and, in the interim, to urge North Sea offshore operators to conclude a voluntary arrangement in respect of compensation for oil pollution damage. OPOL, signed in 1974 and effective the following year, was the result.

OPOL is similar to the 1976 convention, but is limited to $25 million per incident. The agreement is an important part of British law pertaining to compensation for oil pollution damage because it offers an alternative to common law remedies pending the enactment of legislation implementing the 1976 convention. OPOL's strict liability provisions suggest that the agreement would be preferable to the common law as a remedy; however, if aggregated claims exceeded $25 million, a plaintiff might forsake the higher probability of recovery under OPOL to seek full compensation.

CONCLUSION

Front page disasters have concentrated the political will prerequisite to oil pollution control legislation. In March, 1967, when the *Torrey Canyon* grounded off Cornwall, existing legislation was primarily concerned with operational discharges from vessels. However, the *Torrey Canyon* incident and a series of other accidents in the following years greatly changed the legal framework. As a direct result of the *Allegro-Pacific Glory* and *Panther* accidents, the Prevention of Oil Pollution Act, 1971, was expanded beyond its original concern with improvement of operational discharge standards for vessels to include a "Shipping Casualties" section. The Intervention Convention thus incorporated into British law had itself been inspired by the *Torrey Canyon* accident. The Merchant Shipping Act, 1971, implements the 1969 IMCO Civil Liability Convention; the Merchant Shipping Act, 1974, effects the same result with the 1971 Fund Convention. Both conventions resulted from the *Torrey Canyon* disaster. The Mineral Workings Act, 1971, was a legislative response to the catastrophic collapse of a

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uniformity and stability when the dollar was based on gold and members of the IMF were bound to maintain the market value of currencies in relation to gold. However, after 1971, most currencies, including the dollar, were permitted to "float" independent of the gold standard. Bristow, "Gold Franc--Replacement of Unit of Account," 1 *Lloyd's Mar. and Comm. L. Q.* 31 (1978).

mobile drilling platform, the *Sea Gem*. It is probable that the Ekofisk blowout will influence the course of legislation, both in respect of additional regulations concerning the administrative and organizational aspects of offshore operations and as an incentive for early ratification of the 1976 Civil Liability Convention. Moreover, findings by the Liberian and Norwegian Commissions of Inquiry that human error caused the *Torrey Canyon* grounding and was a major contributor to the Ekofisk blowout raise intriguing questions concerning the means and ethics of inducing behavioral changes in a quest for zero-error job performance. Finally, it is thought likely that the U.S. response to the *Argo Merchant (et al.)* casualties, plus the reminder to a nervous Parliament of British vulnerability to such accidents will hasten international acceptance of the 1973 IMCO Convention and consequent U.K. legislation.

A notable characteristic of British oil pollution legislation is its consistency with the terms of international conventions. The Prevention of Oil Pollution Act, 1971, applies terms of the 1954 IMCO Convention and the 1969 Intervention Convention to persons and vessels subject to British jurisdiction. The 1971 and 1974 Merchant Shipping Acts incorporate the provisions of the 1969 Civil Liability Convention and the 1971 Fund Convention into domestic law. New legislation reflecting the terms of the 1973 IMCO Convention and the 1976 Civil Liability Convention is imminent. It is evident that international politics, as well as the national variety, influence the nature and scope of British marine pollution control law.

Finally, one may detect a glimmer of hope from the history of those provisions of the Prevention of Oil Pollution Act, 1971, concerned with operational discharges from vessels. The 1969 amendments to the *1954 IMCO Convention* resulted not from accident, but from careful research at Warren Spring Laboratory. There is a manifest need for further scientific contributions to replace accident with design as a source of British oil pollution control law.

PROPOSALS FOR REFORM IN THE ASSESSMENT OF OIL SPILL DAMAGES

Before

American Institute of Biological Sciences Conference on Assessment of Ecological Impacts of Oil Spills

June 14, 1978

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PROPOSALS FOR REFORM IN THE ASSESSMENT OF OIL SPILL DAMAGES

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ABSTRACT

Despite the increasing public and scientific concern over the potential damage that may be caused by oil spills and other forms of marine pollution, rather little effort has been expended with respect to identifying the particular forms of damage from such incidents that the law will recompense.

The purposes of this paper will be two-fold. First, the types of legally-compensable damage will be catalogued and discussed. Our primary focus here is damage which may occur to the marine environment; in particular, living resources. The scope of damages recoverable by public interests is particularly obscure: do oil spill clean-up costs include the costs associated with damage to natural resources?

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The subject of this paper was initially addressed at the Conference of Oil Spill Damage Assessment, sponsored by EPA and the National Oceanic and Atmospheric Administration (NOAA) at Anchorage, Alaska, in November 1977. Opinions expressed in this paper are those of the authors alone; and no official support or endorsement by EPA, NOAA, or LeBoeuf, Lamb, Leiby & MacRae is intended or should be inferred.

Second, the proliferating mechanisms to ensure payment to damaged parties (e.g., the "Superfund" legislation) do not solve the problem of proving that one's interests have been injured by a spill, and, perhaps even more difficult, in proving the monetary value of the injury. This problem can be addressed in a variety of ways, ranging from continued use of the classical trial model, innovative Federal or state rulemaking, or arbitrary damage figures fixed by statute. An assessment will be provided as to the potential legal and practical difficulties with each of the alternative approaches.

I. INTRODUCTION

In the past several years, much attention has quite properly been paid to the need to ensure that those who are injured by oil spills and other kinds of environmental damage are compensated for the losses they may sustain. This attention has had two principal aspects: first, ensuring that money is available to cover these damages, and second, removing certain procedural hurdles that the law has erected in the past as a bar to recovery in lawsuits. Legislation such as the superfund bill that Lieutenant Couper of the Coast Guard has ably described1/ seeks, in its way, to achieve both of these ends.

At the other end of the process, the scientific community, led by the National Response Team, and other entities such as the American Institute of Biological Sciences, is attempting to mobilize itself to cope with the technical problems of assessing the ecological consequences of major pollution episodes in perhaps a more organized fashion that has characterized past scientific responses to spills. The effort here is to fashion a scientific program that will not merely generate scientific data, but will also provide needed inputs to our practical needs to compensate the injured in an intelligent and not a fictional or arbitrary way.

There are two problems, however, that have not been generally recognized, and for which we feel creative solutions are critically needed and are possible if the promise of scientific inquiry is to be more than a spinning of wheels and if legislation such as the superfund measure is to be more than a delusion. These steps are as follows: first, as much biological research as possible must be performed before, rather than after, an oil spill or other pollution incident occurs. To be sure, the informational baseline cannot be moved completely to a point <u>before</u> the episode, but much work can be done and its results subjected to examination and review in a

forum that will have the attention of the public, that will be adequately funded, and that will, to the extent practicable, be free of the need to function under the emergency conditions that have unfortunately frequently obtained in the past. We must, if you will, move the scientific baseline forward with respect to environmental damage assessment.

The second problem to be recognized is that no amount of compensation funding in the till--even with the removal of some important technical legal hurdles, such as the various defenses that have been honored in the past under some statutes--can by any means guarantee that those dollars will flow to those who are in fact injured by marine pollution. The reasons that such programs may be illusory is that it will still be necessary for pollution claimants to demonstrate that they were in fact injured by a particular spill and to assign a dollar value to those injuries. The problem of causation will occur in any context (barring establishment of an across-the-board rule that, for example, any state in whose waters a spill occurred would automatically be deemed to have been materially injured as a result of the spill). The issue, then, is to determine the dollar value to assign to particular kinds of environmental injury, and to do it in a way that is not arbitrary, that is procedurally fair, that provides a measure of nationwide uniformity and predictability, that is sensitive to the subtleties of sophisticated biology and economics, and that aids claimants by reducing the costs of environmental litigation.

The superfund concept will not cure either of the problems: claimants will still have to show what the natural resource damage is, and to fix a dollar value. In this paper, we shall seek to describe briefly the way the present legal framework deals with these two issues, note the shortcomings in the present system, and suggest alternative ways of addressing these issues in a more rational, more timely and more predictable manner.

II. WHAT DAMAGES ARE COMPENSABLE AND TO WHOM?

A. Jurisdiction

State and Federal governments share jurisdiction over marine resources. By Federal statute, coastal states manage resources in an area at least three miles seaward from shore, subject to the Federal power over navigation, commerce, and the national defense.2/ Historically, most Federal control within the three-mile limit has been based on the commerce power.3/

Jurisdiction is an important concept in the context of oil spill damages, as a public body must have legal jurisdiction before it can assert a claim for money damages on behalf of its citizens. However, as between the Federal and state governments, there is no easy answer to the question of who has paramount control, hence ownership, over marine resources. The states have considerable control over resource management within the three-mile limit, but this control is subject to certain paramount Federal powers.4/

B. The Constitutional Balance of Power

The issue of federalism arises where the Federal government and several state governments have enacted regulations regarding marine resource management. In addition, as discussed below, presently there are separate state and Federal oil spill damage assessment schemes.

The Constitution is the root document from which Federal powers flow; Justice Story, speaking for a unanimous Court in Martin v. Hunter's Lessee, said: "The Constitution, unavoidably, deals in general language.... The instrument was not intended to provide merely for the exigencies of a few years, but was to endure throughout a long lapse of ages, the events of which were locked up in the inscrutable purposes of Providence."5/ The Tenth Amendment provides that all powers "not delegated to the United States by the Constituion...are reserved to the States respectively, or to the people." The states' reserved powers are commonly referred to as the police powers.

The states are constrained in the exercise of their police powers by the constitutional rights of affected individuals. They are similarly restrained by the boundaries inherent in a constitutional scheme that gives supremacy to Federal laws and programs over conflicting state efforts.

III. HOW DAMAGES ARE COMPENSABLE UNDER THE PRESENT SCHEME

A. The State Police Power

Coastal states have traditionally exercised their police power to regulate fisheries adjacent to their shorelines. Control by states over the living resources within their coastal zones was recognized as an important state function in Toomer v. Witsell.6/ Of course, state regulatory measures must be within recognized constitutional constraints.7/ Several years after Toomer, Congress enacted the Submerged Lands Act of 1953, which conferred upon the states ownership of both living and

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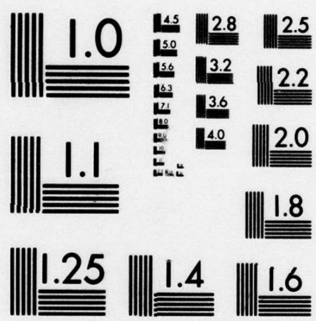

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

nonliving resources within their coastal waters. In sum, the states exercise great control over their marine resources to the seaward limit of their jurisdiction under the Submerged Lands Act. The next question to be explored is the quantum of power that the states can exercise in protecting the quality of their marine waters from oil pollution damage.

1. State Common Law: Parens Patriae

Under the concept of *parens patriae*, a state can act, as trustee of its natural resources, to protect the interests of its citizens.8/ This is not a means for redressing private claims but is limited to actions brought by a public body.

In *Maine v. M/V Tamano*,9/ the State of Maine brought suit in its capacity as *parens patriae* to recover damages for injury to its coastal waters caused by an oil spill. The Court held that the State of Maine had met the test for *parens patriae* capacity by showing (1) that it had an interest apart from that of its citizens and (2) that a substantial portion of its citizens were adversely affected by the challenged act.10/ Thus, the State of Maine was permitted to maintain its action for damages to the waters and marine life of its coastal environment.

Therefore, the doctrine of *parens patriae* is a means by which a state can protect the quality of and resources within its coastal waters. This basis of state power is independent of any state or Federal liability statute and springs from the state's status as a sovereign.

2. State Statutory Measures

Several coastal states have expressed concern for their coastal waters by enacting oil pollution control measures. The majority of state law addresses the matter of oil spill liability and the costs associated with the removal of spilled oil.11/ Largely ignored is the damage caused by the spilled oil to the marine environment. The State of Alaska and the State of Washington are particularly active in the area of oil spill damage and the legislative schemes discussed below reflect their concern.

The Alaska and Washington measures discussed below serve to bridge the gap between simple clean-up costs and clean-up costs that include the additional expense of making the natural system "whole again". This is a fundamental concept of civil tort law. Greatly simplified, the premise is that a person should, at the expense of the wrongdoer, be restored to the status that he or she enjoyed *prior* to the incident.

Professor Dobbs has prepared a scholarly study of legal and equitable damage schemes in his treatise entitled The Law of Remedies.12/ It is interesting to note that absent from this comprehensive text is a discussion of natural resource damage law. The fact that Professor Dobbs' exhaustive work does not include a discussion of natural resource damages is indicative of just how new a concept we are concerned with here.

a. Alaska Dollar-Per-Gallon Act

Recognizing the inherent difficulty in attempting to document the nature and extent of oil spill damages, the Alaska Legislature, in 1977, enacted the "Dollar-Per-Gallon Act".13/ This innovative piece of legislation establishes, albeit arbitrarily, a civil penalty scheme for oil spills. The fine imposed is based on the type and amount of oil spilled and the sensitivity of the receiving waters. Thus, the need to prove actual damages to the marine environment is eliminated.

The Hammond administration is apparently quite pleased with this legislative approach. The State of Alaska recently testified before Congress and suggested that the Alaska scheme serve as a model for proposed amendments to the Outer Continental Shelf Lands Act.14/

The stated thrust of the Alaska legislation is to provide a "meaningful incentive for the safe handling of oil and to insure that the public does not bear substantial (resource) losses from oil pollution".15/ Additionally, the penalties imposed are to "reflect a balance between (sic) the gravity of the discharge, the magnitude of risk, and the level of incentive necessary to induce safe operations". (Alaska Stat. §46.03.758 (a)(3)).

The Act directs the Alaska Department of Environmental Conservation (DEC) to develop regulations establishing a schedule of fixed penalties for discharges of oil. (Alaska Stat. §46.03.758(b)). The DEC is further directed that the maximum penalties which it may establish for certain receiving environments must be within specific limits. These limitations are:

$10 per gallon of oil which enters an anadromous stream or other freshwater environment with significant aquatic resources;
$2.50 per gallon of oil which enters an estuarine, intertidal or confined salt-water environment; and
$1.00 per gallon of oil which enters an

unconfined saltwater environment, public land or freshwater environment without significant aquatic resources.16/

By operation of the statute itself, any such penalty is to be multiplied by a factor of five (5) where the discharge of oil is caused intentionally, by gross negligence, or where a court finds that reasonable measures were not taken to contain and clean up the oil. (Alaska Stat. §46.03.758(b)(2)).

The final penalty criteria to be considered by the DEC are the toxicity, degradability and dispersal characteristics of the spilled oil. (Alaska Stat. §46.03.758 (d)). The penalty formula is to be established by the DEC on a sliding scale, with the maximum penalties (established under §46.03.758(b)) applicable to discharges into the most sensitive and productive of receiving environments. (Id.)

Under this scheme, a spiller is strictly liable for the full amount of the penalties imposed or $100,000,000, whichever is less. (Alaska Stat. §46.03.758(e)). However, liability can be avoided where the spiller can show by a preponderence of the evidence that certain mitigating circumstances were present17/ or that the discharge occurred solely as a result of (1) an act of God; (2) an act of a third person; (3) a negligent or intentional act of the State of Alaska or the United States; or (4) an act of war. (Alaska Stat. §46.03.758(h)).

In sum, the Alaska oil spill liability law establishes fines and penalties for oil spill damages to the state's marine resources. These penalty amounts are the legislature's and the DEC's best guess of what the value of natural resource damage from a prospective oil spill will be. The State of Alaska has taken an important first step in attaching a dollar value to oil spill damages by a creative exercise of the state's police power.

b. Strict Liability by Contract

The body of classical tort law has been developed predominately by judicial action. This is referred to as common law or judge-made law. Various legal doctrines have developed over time based on the premise that the negligent party has a duty to compensate the victim for his or her loss. Generally, it is the body of tort law itself which establishes the rights and duties of people.

A second major body of law under the common law system is contract law, which is governed by different principles from tort law. Under the law of contract,

parties to an agreement can establish what the legal relationship between them will be during the time period that the contract is in effect. By their contract, the parties can within certain limits effectively change the legal relationship that would otherwise exist under the applicable principles of tort law. Thus, a party to a contract may agree to be subject to greater liability than tort law would normally impose. A party may also specifically agree in the contract to waive certain legal rights or defenses. This ability to establish and to change legal relationships by contract or mutual agreement is an important tool utilized by natural resource management agencies.

Nationwide, natural resource management and regulatory agencies have been empowered to function at all levels of government. These agencies may well serve in a dual role, as trustee of the natural environment and as regulator of natural resource use. The legal relationship between such an agency and a resource user is often embodied in a formal written agreement such as a license or permit. The applicant seeking the license or permit may, as a condition of the agreement, have to agree to be held strictly liable for all natural resource damage that may flow from its activities carried out under that license or permit. Should such damage occur, the government body as trustee of public resources would be able to establish the permittee's legal liability without having to prove negligence or fault. In effect, the agreement establishes a no-fault resource damage provision.

Contractual damage provisions have been utilized by the state and Federal government where the government agrees to permit an activity which has an associated environmental risk. Thus, the party contracting with the public body must agree to assume the liability that is associated with the particular activity or the permit will not be granted. Examples of this contract strict liability at the Federal level are found in outer continental shelf oil lease agreements (30 CFR §250.43) and the Agreement and Grant of Right-of-Way for (the) Trans-Alaska Pipeline. (Section 13 (A)(2) and Stipulation 2.5 (1974)). At the state level, the Washington Energy Facility Site Evaluation Council (Energy Council) employs a resource damage provision as an element of its Site Certification Agreements (RCW Chapter 80.50).

In June 1976, the Washington State Energy Council was called upon to enforce the resource damage provision of one such agreement by the Washington Department of Fisheries (Department).18/ The Department, as trustee of the state's food fish and fisheries resources (RCW Chapter 70.08) filed a petition with the Energy Council which

envoked the Council's jurisdiction and alleged salmon fish kill caused by a low flow test conducted by the Washington Public Power Supply System (Supply System) (ORDER at 1).

The resource damage provision of the agreement states as follows:

> The Supply System agrees to provide replacement and/or compensation as found to be necessary by the Council for any wildlife, fish and other aquatic life and ecosystem damage or loss caused by project construction and operation. (Emphasis added). (The Site Certification Agreement between the State of Washington and the Washington Public Power Supply System for Nuclear Projects Nos. 1 & 4 at §IV(d)(1) (August 8, 1975).)

On February 14, 1978, the Energy Council issued its order and found the Supply System liable for the natural resource damage. The order noted that, while it was "technically impossible to replace the fish lost...(the fish could)...be compensated for." (ORDER at 13). The Energy Council ordered the Supply System to construct and operate a fish hatchery for a four-year peiod. The hatchery was to be designed to produce and release 834,000 salmon fry each year. (ORDER at 14). Additionally, the hatchery was to be operated by the Department and all expenses of operation were to be paid by the Supply System. (ORDER at 15).

The Supply System has requested judicial review of the Energy Council's order and there has been no judicial determination to date.19/ This precedent-setting decision of the Washington Court will, in large measure, determine the future validity of the Energy Council's resource damage provision.

The next section of this paper will review the body of Federal law that is relevant to the area of natural resource damage assessment.

B. Federal Law

1. Overview

The history of Federal involvement in the area of marine environmental regulation provides an interesting baseline against which to assess the probable success of any proposed damage assessment mechanism. The Federal government was not significantly involved in environmental

regulation until the passage of the Federal Water Pollution Control Act of 1948. (Ch. 758, §102, 62 Stat. 1155). For the next twenty-one years, Federal regulation was spotty; Congress was satisfied to take a back seat to the states in environmental regulation. However, in 1969 the Stratton Commission report20/ and in 1970 the National Estuarine Pollution Study21/ concluded that state action alone was not enough and that Federal participation was needed. Thus, in 1969 and in the early 1970's, there was a flurry of activity in Congress which resulted in the creation of a body of Federal environmental law.

The various regulatory measures that comprise the body of Federal oil spill damage law are the Clean Water Act of 1977 (Pub. L. No. 95-217, 33 U.S.C. §1251 et seq.), the Trans-Alaska Pipeline Authorization Act (43 U.S.C. §1651 et seq.), the Deep Water Port Act of 1974 (33 U.S.C. §1501 et seq.) and the Outer Continental Shelf Lands Act (43 U.S.C. §1331 et seq.). Appendix A provides a matrix of this body of law and includes several important newly proposed laws.

The matrix, entitled "Federal Laws Relevant to Oil Spill Damage Assessment", sets out the key elements of the oil spill liability schemes provided under both existing and proposed legislation. Additionally, the matrix highlights the natural resource damage provisions of the various laws. The major Federal law discussed below is the Clean Water Act of 1977 (CWA). This Act will be examined first as an oil spill liability scheme, and secondly as a natural resource damage control measure.

2. The Clean Water Act of 1977

a. The CWA as an Oilspill Liability Scheme

The CWA is the primary Federal law governing oil spills. Through this Act, Congress declared it to be the national policy that:

> there shall be no discharge of oil or hazardous substances into or upon the waters of the contiguous zone, or in connection with activities under the Outer Continental Shelf Lands Act or the Deepwater Port Act of 1974, or which may affect natural resources belonging to, appertaining to, or under the exclusive management authority of the United States (including resources under the Fishery Conservation and Management Act of 1976). (Emphasis added) (33 U.S.C. §1321(b)(1)).

Prior to the enactment of the 1977 Amendments to the Water Act, the seaward reach of section 1321 was limited to the contiguous zone, which is roughly twelve miles from the coast. By the CWA, the United States has unilaterally extended its oil pollution control jurisdiction generally to 200 miles from the coast. Thus, the pollution control zone is coextensive with the fishery management zone established by the Fishery Conservation and Management Act of 1976 (Pub. L. No. 94-265, 90 Stat. 331, 16 U.S.C. §1801 <u>et seq</u>.).

Under the CWA, the President acting through the U.S. Environmental Protection Agency (EPA) (Executive Order 11735 (1973)), has the task of determining what discharges of oil or hazardous substances are "harmful" and promulgating regulations to the effect. (33 U.S.C. §1321(b)(3) and (4)). Harmful quantities of oil have been defined as those which: "(a) violate applicable water quality standards, or (b) cause a film or sheen upon or discoloration of the surface of the water or adjoining shorelines or cause a sludge or emulsion to be deposited beneath the surface of the water or upon adjoining shorelines."22/

Not all discharges of oil are covered by the Act; there are two areas specifically exempted. The first area includes discharges "into the waters of the contiguous zone, where permitted under the International Convention for the Prevention of Pollution of the Sea by Oil, 1954." (33 U.S.C. §1321(b)(3)(A)). The second covers discharges which are "permitted in quantities and at times and locations or under such circumstances or conditions as the the President may, by regulation, determine not to be harmful." (33 U.S.C. §1321(b)(3)(B)).

The CWA establishes a liability scheme concerning oil discharges which violate the Act. The discharger is strictly liable for a limited amount of the actual cost of clean-up incurred by the United States.23/ Owners or operators of any vessel from which oil is discharged in violation of the Act are liable "for the removal of such oil...in an amount not to exceed, in the case of an inland oil barge, $125 per gross ton of such barge, or $125,000, whichever is greater, and in the case of any other vessel, $150 per gross ton of such vessel (or, for a vessel carrying oil or hazardous substances as cargo, $250,000), whichever is greater." (33 U.S.C. §1321(f)(1)). Owners or operators of both onshore and offshore (33 U.S.C. §1321(f)(2) and (3)) facilities are liable to the United States for the cost of removal of the oil in an amount up to $50 million. The cost of removal includes any costs or expenses incurred by the Federal or any state government in the <u>restoration or replacement of natural resources</u> damaged or destroyed as a result of the discharge. (33 U.S.C. §1321(f)(4)).

Liability can be avoided only where the discharge is proven to be the result of "(a) an act of God, (b) an act of war, (c) negligence on the part of the United States government, or (d) an act or omission of a third party without regard to whether any such act or omission was or was not negligent, or any combination of the foregoing clauses." But, where it can be proven that the discharge was the result of "willful negligence or willful misconduct with the [party's] privity and knowledge", the amount of liability is unlimited. (33 U.S.C. §1321(f)(1)-(3)).

Civil penalties of up to $5,000 for each offense are available under the Act when oil is discharged in harmful quantities. Moreover, when a discharger fails to notify the appropriate Federal agency, criminal sanctions are available. (33 U.S.C. §1321(b)(5) and (6)). All self-propelled oil tankers over three hundred gross tons utilizing United States waters or ports are required under the Act to maintain proof of financial responsibility. The degree of financial responsibility that must be demonstrated is dependent on the vessel type and size. In the case of an inland oil barge, the degree of financial responsibility is $125 per gross ton of such barge, or $125,000, whichever is greater, and in the case of any other vessel, the degree of financial responsibility is $150 per gross ton of such vessel (or, for a vessel carrying oil or hazardous substances as cargo, $250,000), whichever is greater. (33 U.S.C. §1321(p)(1)).

The Federal Maritime Commission recently proposed new regulations to provide for vessel financial responsibility in accordance with the CWA. (43 Fed. Reg. 16772-83 (April 20, 1978)). These proposed regulations, which will become effective on October 1, 1978, recognize the need for broadening the scope of vessel operators' liability for oil spill removal costs; especially since such costs now include the expenses associated with the restoration or replacement of damaged natural resources. (Id at 16773). Unfortunately, the proposed regulations provide no guidance as to what degree of financial responsibility is needed to cover this new category of liability.

Section 1321(c)(2) requires that the President prepare and publish a National Contingency Plan providing for the removal of oil spills. The purpose of this plan is to "provide for efficient, coordinated, and effective action to minimize damage from oil and hazardous substances discharges." (33 U.S.C. §1321(c)(2)). The plan is to be used whenever an oil spill occurs unless the President determines that the party responsible for the discharge is capable of properly removing it.

The President is directed to give the National Contingency Plan the force of law by issuing "regulations consistent with maritime safety and navigation laws." The Act also provides for civil penalties in the event that a party fails to comply with regulations promulgated under the Act. (33 U.S.C. §1321(j)(1) and (2)).

Under Executive Order 11735, the Council on Environmental Quality (CEQ) was charged with the responsibility of preparing a National Oil and Hazardous Substances Pollution Contingency Plan. The National Contingency Plan has been completed (40 CFR Part 1510), and a number of Regional Contingency Plans have been prepared to provide for its implementation. The EPA has the task, under the National Plan, of providing expertise in oil spill damage assessment. (40 CFR §1510.22(1)). The relevant section, entitled "Federal responsibility", states in part that:

> The Environmental Protection Agency, through the Office of Water and Hazardous Materials, provides expertise regarding environmental effects of pollution discharges and environmental pollution control techniques, including assessment of damages. (Emphasis added).

In February 1977, the Subcommittee of the House Committee on Government Operations held hearings to review the National Oilspill Contingency Plan. At these hearings, it was apparent that EPA felt that the assessment of damages resulting from oil spills was a major weakness of the National Plan.24/ This position is shared by others, most notably the U.S. Fish and Wildlife Service and the National Oceanic and Atmospheric Administration (NOAA).25/

One major problem is funding, as neither the Water Act nor the National Plan allows Federal agencies to recover costs for damage assessments conducted as a result of oil spills. At the hearing, Dr. Robert M. White, the former Administrator of NOAA, expressed his concern that pre-spill damage assessments should be prepared to reduce impacts from oil spills in areas crutial to the survival of fishery resources.26/

We suggest that both the pre-spill and post-spill types of biological assessment are important from a legal viewpoint. As to the cost of such a study, one possible solution would be that the spiller bear a fair portion of the financial burden. It certainly can be argued that the spiller is responsible for the post-spill study costs which relate to the assessment of the damage caused by

the spill. This approach, however, may present a legal problem in that the taxing of one person for an activity of general benefit may be objectionable in light of two recent U.S. Supreme Court decisions concerning administrative agency license fees. (National Cable Television Assoc., Inc. v. United States, 415 U.S. 336 (1974); Federal Power Comm. v. New England Power Co., 415 U.S. 345 (1974)).

b. The Natural Resource Damage Provisions of the Clean Water Act of 1977

Although the Federal government has been actively involved in water pollution control since 1948, it did not address the problem of natural resource damages until enactment of the 1977 Clean Water Act (CWA). In particular, section 1321 of the CWA now embraces natural resource damage within the scope of oil spill clean-up costs. Prior to the passage of the CWA, a spiller's liability under section 1321(f) was for the actual costs incurred by the Federal government in removing the oil in accordance with section 1321(c)(1). Such removal is defined by the CWA as the "removal of the oil...from the water and shorelines or the taking of such other actions as may be necessary to minimize or mitigate damages to the public health or welfare". (33 U.S.C. §1321(a)(8)).

Subsection 1321(f)(4) is the major new provision which, in the authors' opinion, helps to set the stage for a new era in the development of Federal environmental law.27/ This subsection states that:

> The costs of removal of oil or a hazardous substance for which the owner or operator of a vessel or onshore or offshore facility is liable under subsection (f) of this section, shall include any costs or expenses incurred by the Federal government in the restoration or replacement of natural resources damaged or destroyed as a result of a discharge of oil or a hazardous substance in violation of subsection (b) of this section. (Emphasis added).

Another new subsection of section 1321, section (f)(5) mandates that the President or an authorized state representative "act on behalf of the public as trustee of the natural resources to recover for the costs of replacing or restoring such resources". (33 U.S.C. §1321(f)(5)). The legislative intent behind the adoption of the natural resource damage provisions of sections 1321(f)(4) and (5) is set out in the Conference Committee Report. The Report, in explaining the liability associated with these new provisions, stated that:

> For those resources which can be restored or rehabilitated, the measure of liability is the reasonable costs actually incurred by Federal or state authorities in replacing the resources or otherwise mitigating the damage. Where the damaged or destroyed resource is irreplaceable (as an endangered species or an entire fishery), the measure of liability is the reasonable cost of acquiring resources to offset the loss. (H.R. Rep. No. 95-830, 95th Cong., 1st Sess. 92 (1977)).

Perhaps the most interesting statutory language in this subsection appears in section 1321(f)(5) where Congress has said that "[s]ums recovered shall be used to restore, rehabilitate, or acquire the equivalent of such natural resources by the appropriate agencies of the Federal government or the state government." (Emphasis added.) The procedural sequence of events, triggered by section 1321(f)(5), provides the key to making the new natural resource damage provision work. This is because the trustee for the environment must first assess or expend monies to rectify the natural resource damage caused by the spill before the trustee may add these costs to the overall government claim for "costs of removal" (33 U.S.C. §1321(f)(4). The cost associated with natural resource damage is not available from the revolving fund established under section 1321(k). The language of the CWA is unclear as to whether the trustee must first expend funds to restore or replace the environment before these costs can be assessed against the spiller. A second interpretation is that the environment can be restored only after the government has prevailed in court and the spiller has paid the money damages awarded by the court (33 U.S.C. §1321(f)(5)).

This new provision in the Water Act is encouraging, but one must reflect on this development in a broader context. The question remains as to whether there is adequate information presently available to implement the restoration and replacement provisions of the Act. An important concept to keep in mind is that natural resource damage by oil spill is only a small part of the total picture. The prospective damage that may be caused by hazardous or toxic substances may pose substantially more difficult natural resource damage questions.

In the authors' opinion, however, even with the first hurdle of fixing liability behind us, a more formidable barrier appears in our path. This is the problem of placing a monetary value on the natural resources damaged by the spill. Below, we will suggest some proposals that

may be employed in conducting such a valuation process. Once developed, this proposed valuation scheme can be utilized to fix a dollar value on natural resource damage regardless of the cause of such loss.

IV. SOME PROPOSALS FOR CHANGE

A. The Valuation Process

As we have indicated, a central shortcoming of the present institutional arrangements for compensation of victims of oil spills is the litigative burden of showing the value of such injury. Each claimant would have to prove individual damages--a task that is costly, time-consuming and inherently uncertain. For the public claimant for damage to natural resources--such as the Federal government or a state--this shortcoming presents serious problems; even less tolerable are the problems which confront the smaller public claimant or the private claimant. Defendants in spill cases also have an obvious interest in the matter. The issue, then, is whether there is some way to streamline this process by developing some "neutral principles" of damage assessment and if possible by assigning some conventional value to such injuries in advance, and thereby in whole or in part drop this element of proof out of the controversy in the event of post-spill claims.

But can such things be precisely valued? The answer here is that we think fair nonjudicial methods of valuation are feasible and should at least be considered.

There are numerous illustrations of attempts to set a hard-and-fast value on particular forms of wildlife.28/ For example, the Pollution Committee of the Southern Division of the American Fisheries Society has published a pamphlet entitled "Monetary Values of Fish", the 1975 revision of which commences with the observation that "[e]very fish has a value". The booklet goes on to state quite properly that "[t]he compensation for the loss of fish due to water pollution mandates a readily accessible table of values for fishes of all species". That listing may be faulted on the ground that it is based only on a survey of average purchase prices charged by the commercial fish hatcheries. Hatchery prices may be an imperfect guide to values--on this economists will surely differ and we need not resolve the issue here--but the very fact that AFS has produced this guide suggests that we need not reinvent the wheel in each damage assessment situation. Happily, we understand that AFS is considering further regional and nationwide efforts along the same lines. But numerous questions remain. How often must the values be revised to reflect the impact of inflation?

Are per-fish or per-pound values useful without also taking into account the costs of transportation, assessment and restocking? Is it necessary to consider both hatchery prices and commercial fish prices, at least for food fish for which a market exists? How shall we treat special cases such as endangered species? The American Fisheries Society table assigns what appears to be an arbitrarily selected value of $51.00 per pound for all sizes of five different sturgeons, offering as support the following comment in a footnote: "Most members of this family are considered to be rare and should be protected, hence the high value assigned". This AFS table has been cited in connection with the preparation of benefit-cost analyses under the National Environmental Policy Act of 1969,29/ but it is not definitive and has no independent legal status.

Another approach is evident in the Principles and Standards for Planning Water and Related Land Resources, promulgated by the Water Resources Council in 1973.30/ Under those guidelines, an effort is made to assign per day values to recreational activities including recreational fishing. The guidelines, with which many of you may already be familiar, divide outdoor recreation into two categories. The general category, which is said to include a value range of 75-cents to $2.25, involves "primarily those activities attractive to the majority of outdoor recreationists and which generally require the development and maintenance of convenient access and adequate facilities". The other category (entitled "specialized") is assigned a daily value range of $3.00 to $9.00, and is defined to involve "primarily those activities for which opportunities, in general, are limited, intensity of use is low, and often may involve a large personal expense by the user". The difference between the two categories may be difficult to define, but one may be tempted to invoke, by analogy, Mr. Justice Stewart's celebrated dictum concerning obscenity31/-- namely, that, however difficult it is to define a specialized form of recreation, one nonetheless knows it when one sees it. For example, the gentleman bass fisherman fully outfitted by Abercrombie and Fitch is presumably (by the Water Resources Council's lights) to be distinguished from the modern day Huck Finn with a nightcrawler-laden drop line at the end of the dock on a sleepy summer afternoon.

How useful are the Water Resources Council guidelines? Aside from the inflation occurring since 1973, both categories--general and specialized--provide only a range of values, indeed a range where the ceiling is three times the minimum. For a claimant or a putative defendant in a major pollution case a potential recovery range of 3:1 is

rather broad, although one may be tempted to observe that even this kind of uncertainty is a real improvement over what would otherwise be the case. Two additional observations must be offered with respect to these guidelines, one procedural and one substantive. First, they were developed through the rulemaking process provided under the Administrative Procedure Act. Thus, they were issued in proposed form and followed "extensive study, review, field testing and public hearings" as well as preparation of an environmental impact statement. In these respects, the public participation in the rulemaking may provide a model for future generic actions with respect to damage assessment valuation problems. The other observation is that even if a two-category breakdown may not do justice to the variety of economic values in issue in marine pollution valuation efforts, the notion of a ceiling is an important way of dealing with the problem of the recreational expenses of the sportsman who is not so much an enthusiast as a fanatic. No system of compensation should recompense those whose outlays are patently unreasonable.

Implementation of the Water Resources Council Principles and Standards, incidentally, will be revised in the next twelve months under an initiative announced by President Carter on June 6, 1978. In particular, the President has directed the Council "to prepare a manual which ensures that benefits and costs are calculated using the best techniques and provides for consistent application of the Principles and Standards and other requirements".32/ Perhaps the Administration's new initiative with respect to the Principles and Standards will carry over into a further refinement of the problem of valuation of natural resources and access to them. The scientific community, particularly including this audience, should be aware of developments such as these not only because they will have an impact on Federal construction projects (which they will), but also because they can have an important, albeit indirect, effect on other Federal decision-making such as the issuance of licenses for various private projects that require Federal or state approval. Of course, whether it is proper to apply the Principles and Standards in this broader field will be a function of the quality of the data that go into their formulation, the existence of procedural mechanisms that would make them applicable as a legal matter, and the sufficiency of the procedures used for their formulation.

B. Institutional Mechanisms Available

It is possible to identify several potential vehicles for achieving the dual objectives we have postulated

(i.e., moving the damage assessment baseline forward in time and regularizing the process of damage assessment evaluation to reduce the litigative burden and the range of uncertainty). Some of these alternatives are as follows:

First, one can pass a new statute that will determine natural resource damages in a more or less arbitrary way, along the lines of the Alaska dollar-per-gallon law.33/ This is, to be sure, a direct way to do things, but what it gains in certainty it may well lose in fairness. Fundamentally, it constitutes a legislative shrug, a throwing up of the hands and a basic lack of confidence in the ability of scientists and economists to describe reality, including the complex reality of the environment. Another shortcoming of the legislative fiat approach is that it is rather rigid; once passed, it can be dreadfully difficult to obtain further legislation to correct, modify or update a law. And significantly, with respect, legislative committee hearings are probably not suited, as a general rule, to the development of the kind of detailed factual record that an administrative agency can develop using skilled staff.

Second, one can attempt to impose damage assessment rules by contract, for example, as a condition to a Federal or state permit or lease. This has been done in several contexts. Even so, the contract route for fixing damages in advance is not available in all cases. Another shortcoming is the fact that such liability without fault provisions may be imposed in an unfair way given the uneven bargaining power of the parties, and may be no less arbitrary than the dollar-per-gallon approach noted previously. While the contract option may provide a way, then, to reach the party at fault, it does so in a manner that may be inflexible, scientifically unsupportable, and quite summary in nature.

A rulemaking approach may be a preferable alternative. Consider, for example, the possibility that the activity that President Carter has directed the Water Resources Council to undertake could be the occasion for a broader reform of decision-making methods and institutions in the damage assessment area. This assumes a fundamental kinship between the benefit-cost analysis required for Federal projects and the damage assessment process as it relates to conduct which is merely licensed or permitted, or conduct that is unintended (such as oil spills). The core biological issues here may be similar, but the economic and public policy issues in building a dam or some other expenditure of public funds, may not necessarily be either so wise, so fair or so legal where the disposition of private property is concerned.

If the upcoming efforts of the Water Resources Council are to serve these broader damage assessment/valuation purposes (a circumstance which would require a broadening of the Council's present mandate), it would call for the involvement of the scientific community in a more pervasive way than we believe may have been the case in past Council efforts. In addition, if the broader damage assessment issues related to oil pollution are to be explored under the aegis of the Council's forthcoming effort, there must be substantial opportunity for public participation. We hasten to add, however, that even if the Council effort were expanded beyond a concern with purely Federal projects, lacking clear statutory foundation that would give it "teeth", it would probably prove to be of little practical value in the assessment of real-life oil spill damage to natural resources. We also fear that the one-year deadline imposed by the President would clearly not be adequate for the achievement of anything more than the creation of an institutional framework for the streamlined process of damage assessment which we believe is needed.

The Water Resources Council may not be the proper body to perform the function we have in mind. Perhaps a preferable alternative would be for the inquiry we have suggested to be led by the National Response Team (NRT), which is one of the government's most appropriate sources of biological expertise that would be so critical if the damage assessment baseline is to be moved forward. The NRT is not currently involved in rulemaking activities of the sort we have in mind, and it would be unfortunate if it became burdened down under the weight of such regulatory tasks. It might in this respect be better for an agency that already has rulemaking or related functions to provide the forum for a damage assessment and valuation rulemaking, with the NRT and other interested and qualified agencies of the government, and the states and private parties, to participate as full parties to the administrative proceedings.

C. Prospective Role of the Fishery Management Councils

The Regional Fishery Management Councils created under the Fishery Conservation and Management Act of 1976 34/ could also be considered in this regard, either as parties or conceivably as the rulemaking agency, to reflect the regional dimension of marine natural resource damage assessment.

In expanding the scope of section 1321 of the CWA, Congress stated that it is "the policy of the United States that there should be no discharges of oil...which may affect natural resources belonging to, appertaining

to, or under the exclusive management authority of the United States (including resources under the Fishery Conservation and Management Act of 1976)". (33 U.S.C. §1321(b)(1)). This section of the CWA is clearly intended to protect from pollution by oil the natural resources which had been previously claimed by the United States under the Fishery Conservation and Management Act of 1976 (Fishery Act) (Pub. L. 94-265, 16 U.S.C. §1801 et seq. (1976)). It may well be that the Fishery Act can be utilized in conjunction with the CWA to provide the indicia of natural resource protection envisioned by Congress in enacting the CWA.

In enacting the Fishery Act, Congress specifically found that the "fish off the coasts of the United States ...constitute valuable and renewable natural resources. These fishery resources contribute to the food supply, economy, and health of the Nation..." (16 U.S.C. §1801(a)(1)). Based on this and other findings (16 U.S.C. §1801(a)(5),(6)), Congress then unilaterally expanded seaward the jurisdiction of the United States for fishery management purposes (16 U.S.C. §1811). The Fishery Act claims exclusive authority to manage all forms of marine animal and plant life, other than marine mannals, birds, and highly migratory species within a 200-mile Conservation Zone (16 U.S.C. §1801(b)(1), and §1802(1),(3)-(4)), and beyond, where the Continental Shelf extends seaward of the 200-mile zone. (16 U.S.C. §1812).

The Act establishes eight Regional Fishery Management Councils and charges them with the responsibility to develop fishery management plans designed to conserve and manage these fishery resources (16 U.S.C. §1801(b)(1),(4)). The Council's task of conservation and management includes inter alia, measures taken to rebuild, restore, or maintain any fishery resource of the marine environment (16 U.S.C. §1802(2)).

These Fishery Management Councils are established pursuant to section 1852(a) of the Act and are charged with responsibility for the development of a fishery management plan for each fishery within its jurisdiction (16 U.S.C. §1852(h)(1)). These various plans must be prepared in a manner consistent with a set of seven national standards (16 U.S.C. §1851(a)). Certainly, in order to properly carry out its management role, a council must know the nature of the resource that it seeks to manage. The knowledge gained by the Council could readily be used for the development of baseline damage assessment data. Moreover, under section 1852(g)(2), the Councils have authority to "establish such other advisory panels as are necessary or appropriate to assist it in carrying out its functions under (the Act)".

Thus, the Fishery Management Councils are in the unique position to orchestrate the natural resource valuation process. The Councils, which enjoy a joint Federal-state status, have both the expertise and the practical management experience to conduct this valuation exercise.

D. Proposals to Implement Rulemaking

Assuming that a rulemaking approach is preferable to a more rigid statutory approach, what should these proceedings entail? Here two approaches are possible. Either the proceeding would conclude by issuing a regulation that provides a conventional dollar value for particular natural resources (something we call a Federal Presumptive Value, or FPV), that would directly govern the disposition of claims. Or it would result in issuance of a Federal regulation that would constitute a guideline for states to use in developing Natural Resources Damage Assessment Plans (NARDAP) that would in turn establish conventional dollar values for particular natural resources or types of injury to those resources. This would provide a measure of uniformity in principle, but it must be recognized that a substantial amount of interstate diversity would be inevitable. Beyond this, the fact that the states would, to a degree, be judging their own cases (since they too would be potential damage claimants) suggests that delegation of this sort, in this context, would not be without serious drawbacks, and would arguably be unconstitutional.35/

Under the National Coastal Zone Management Act of 1972 (16 U.S.C. §1451 et seq.), a state may develop a coastal zone management program. This Act could provide a model for the development of a joint Federal-state damage assessment scheme. Such a scheme would consist of a state-developed Natural Resource Damage Assessment Plan (NARDAP), prepared in conformity with Federal criteria. Use of Federal criteria would foster the development of uniform state approaches to damage assessment. Damages assessed in accordance with a federally-approved NARDAP could be given priority in "superfund" disbursements.

The major problem with this approach is that either some states may choose not to prepare such a plan or those that choose to develop a plan may not prepare an adequate one. The Coastal Zone Management Act provides for voluntary state participation, and an approved state plan exists only as a matter of state law.

On the other hand, under the Clean Air Act (Pub. L. No. 95-95 (1977)), the Federal agency which administers the Act (EPA) has the authority to promulgate a State

Implementation Plan (SIP) where the state does not. Moreover, once a state implements its state plan as a matter of state law it may be submitted to EPA for approval as a part of the SIP. Once approved, the revision to the SIP exists as a matter of state law and as Federal law. Additionally, the provisions of the Clean Air Act may generally be enforced by either the state or by EPA. Therefore, the Air Act may serve as a better example of how a state/Federal NARDAP may be developed and implemented.

Whichever route is adopted, the resultant rule or standard should be made binding on administrative or judicial decision-makers in cases of oil spill damage assessment, subject to adjustment for such factors as the Consumer Price Index. This would force the interested parties to focus their attention on the administrative proceedings to be conducted before technically competent officials who would, with appropriate procedural safeguards, provide a more suitable forum for the resolution of generic natural resource damage assessment issues than would a United States District Court. In the event there was no applicable rule or standard that could apply to a given type of natural resource damage assessment problem, a claims-administration agency or court with jurisdiction could stay its hand until the matter had been referred to the proper *administrative agency and a rule or standard* developed in that context.

Such rules or standards would be subject to judicial review on limited grounds such as arbitrariness or lack of substantial evidence, although it is to be expected that they would also be challenged as a deprivation of the right to a judicial determination of damages or as a taking without just compensation or due process. Given the acknowledged validity of measures such as the Federal Longshoremen's and Harbor Workers' Compensation Act36/ or the workmen's compensation laws, which involve the use of schedules setting for specific payments for particular injuries,37/ one would expect the program we have outlined to pass constitutional muster--assuming fair rulemaking procedures are used and an adequate record is made--even though there will inevitably be debate over whether some quid pro quo is needed and whether, if one is needed, it has been provided.

V. CONCLUSION

In a thoughtful book entitled Economics and the Environment--A Materials Balance Approach, Messrs. Allen V. Kneese, Robert U. Ayres and Ralph C. d'Arge offered the following observation with respect to the institutional arrangements for dealing with environment and economic issues:

> No amount of natural or social science research will help us deal with our environmental problems unless we learn how to implement effective management programs through legal and political institutions. How can we provide for a framework of incentives to compensate for powerful institutional intekests in the status quo? How can we arrange institutions which comport with the diverse regional boundaries of the technological and economic aspects of environmental problems, whose patterns of representation press toward achieving the desired ends of man to the maximum extent, and which at the same time meet legal and political criteria of justice and equity? Surely these are the most difficult and least understood issues we have yet raised. (Emphasis added).

We believe that these are perhaps the central issues that should be confronted by this audience, whether you are associated with the government, academia, the environmental movement, or the industrial sector. In offering our suggestions today, the authors wish to emphasize our recognition of the presence of important scientific, legal, and policy issues in what we have proposed. To what extent can natural resource damage assessment be performed in advance? Certainly the experience with the National Environmental Policy Act's environmental impact statement process illustrates that much can be done before the fact, despite whatever reservations one may have about the way that process has taken shape.

On another level, to what extent is it likely that academia or the Federal or state governments will provide funding for the scientific and economic effort and administrative proceedings that would be necessary to fulfill our plan? Is the natural resource damage assessment "caseload" sufficient to justify the kind of expense that would be involved in what we have proposed? That is, is the game worth the candle? And legally, one may wonder whether the plan we have suggested is constitutional, or whether on the contrary it intrudes upon or truncates the right to a judicial proceeding for the determination of legal damages. Would a limitation on liability withstand constitutional challenge in the present legal climate? Is a nationwide approach necessary, appropriate or scientifically and economically feasible, or would a regional approach have more to commend it? Finally, can or should attention be given to the possible international implications of a generic approach to natural resource damage assessment issues?

We by no means claim to have the answers to all of these questions, but we mention them so as not to add to the euphoria which some may already feel in the face of the superfund bill and other measures that hold forth the promise of assured payment for claims for damage to natural resources. Whether or not such a "superfund high" is warranted, we hope that discussion will be encouraged by our suggestion, and if there be agreement as to the need for changes in the way the scientific, governmental and legal communities have addressed these matters, we further hope that the institutional changes we have proposed, which are in important respects not unlike a recent proposal by the National Advisory Committee on Oceans and Atmosphere,38/ will be found worthy of detailed consideration.

FOOTNOTES

1. See Couper, The Comprehensive Oil Pollution Liability and Compensation Act: An Update (1978).

2. Submerged Land Act of 1953, 43 U.S.C. §§1301-1303, 1311, 1314 (1970).

3. See, e.g., Gibson v. United States, 166 U.S. 269, 271-72 (1897).

4. U.S. Const. art. VI, cl.2.

5. 14 U.S. (1 Wheat.) 562, 564 (1816).

6. 334 U.S. 385 (1948). Accord, State of Maryland v. Amerada Hess Corp., 350 F. Supp. 1060 (D. Md. 1972). See also Corsa v. Tawes, 149 F. Supp. 771 (D. Md.), aff'd, 335 U.S. 37 (1957).

7. This case is better known for the fact that the Court struck down disproportional license fees on out-of-state fishing boats as violating the priviledges and immunities clause and invalidated a stamp tax as imposing a undue burden on interstate commerce. Toomer v. Witsell, supra note 6 at 395-407.

8. The concept of parens patriae has been embodied in §1321 of the Clean Water Act of 1977. This Act is discussed infra at §III.B. For a more detailed analysis of state oil spill control measures, see DOJ Study prepared for the Senate Comm. on Commerce, 94th Cong., 1st Sess., Methods and Procedures for Implementing A Uniform Law Providing Liability for Clean-up Costs and Damages Caused by Oil Spills from Ocean Related Sources 35-37 (Comm. Print 1975).

9. 357 F. Supp. 1097 (D. Me. 1973).

10. Id. at 1099-101.

11. For a more detailed study of this area of law, see Du Bey, Control of Oil Transport in the Coastal Zone: A Look at Puget Sound, 56 Oregon L. Rev. 593 (1977).

12. D. Dobbs, The Law of Remedies (1973).

13. Alaska Stat. §46.03.758 (Supp. 1977). This Act became effective on September 13, 1977.

14. Sen. Comm. on Energy and Natural Resources, Outer Continental Shelf Land Act Amendments of 1977 (S. 9), No. 95-44, 95th Cong., 1st Sess. 556 (1977).

15. Alaska Stat. §46.03.758(a)(2) (Supp. 1977).

16. Id. at §46.03.758(b)(1)(A)-(C). Section 46.03.758(f) allows a court to deduct from the penalty amount that amount of spilled oil which was subsequently removed from the environment by clean-up operations.

17. Id. at §46.03.758(g). This provision goes on to direct the Court that it:

> shall recognize that scientific knowledge pertaining to oil spills is very limited and if there is insufficient knowledge either to predict a base case or to show mitigating circumstances varying from that base case, the administratively established schedule of penalties shall apply... (Id.).

18. In re Enforcement of Certification Agreement WNP 1 and 4, Washington State Energy Facility Site Evaluation Council, Order No. 544 (1978).

19. Seattle Times, Feb. 18, 1978, §B at 10, col. 4; id. Mar. 17, 1978, §C at 1, col. 2.

20. U.S. Comm'n on Marine Science, Engineering, and Resources, Our Nation and the Sea 4, 56 (1969).

21. U.S. Dep't of the Interior, The National Estuarine Pollution Study, S. Doc. No. 58, 91st Cong., 2d Sess. 368-69 (1970).

22. 40 CFR §110.3 (1977). A visible sheen is informally defined as 10 to 20 parts per million of oil. National Bureau of Standards, U.S. Dep't of Commerce, Marine Pollution Monitoring (Petroleum) 36 (1974) (Special Publication No. 409). See also, 43 Fed. Reg. 10474 et seq. (Mar. 13, 1978), where in accordance with §1321(b)(2)(A) of the CWA, the Administrator promulgated final rules which designated as hazardous substances a number of elements and compounds. When discharged, these materials are deemed to present an imminent and substantial danger to the public health or welfare. Examples of this danger include injury to fish, shellfish, wildlife, shorelines and beaches. (Id.).

23. 33 U.S.C. §1321(b)-(j) (1977). Vessel liability under §1321 of the CWA is not limited by the Limitation of Liability Act, 46 U.S.C. §§181-189 (1958); Accord Complaint of Steuart Transportation Co., 435 F. Supp. 789, 805 (E.D.Va. 1977).

24. Subcomm. of the House Comm. on Government Operations, Oilspill Contingency Plan, 95th Cong. 1st Sess. 288 (Comm. Print Feb. 1977).

25. *Id*. at 37-38, 47.

26. *Id*. at 37.

27. 33 U.S.C. §1321(f)(4) builds on the foundation that has already been provided by the Outer Continental Shelf Lands Act, 43 U.S.C. §1331 *et seq*. (1975); 30 CFR §250.43 (1977); the Trans-Alaska Pipeline Authorization Act, 43 U.S.C. §1651 *et seq*. (1975), 43 CFR §29.1(d) (1976); and the Deepwater Port Act of 1974, 33 U.S.C. §1501 *et seq*. (1975) In particular see §1517(i)(3) of the Deepwater Port Act. *See generally* Appendix A.

28. *See generally* Report of the Comptroller General of the United States, Total Cost Resulting From Two Major Oil Spills (CED-77-71) (June 1977). This report was conducted at the request of Representative Leo J. Ryan, Chairman, House Government Operations Committee in conjunction with the hearings regarding the National Contingency Plan. See note 24 *supra*. *See also* Gosselink, Odum & Pope, The Value of the Tidal Marsh (Louisiana State University, 1974).

29. 42 U.S.C. §4321 *et seq*. (1970); *see, e.g.*, 1 Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Comm'n, Final Environmental Statement Related to Operation of Indian Point Nuclear Generating Plant Unit No. 3 at XI-63 (Feb. 1975).

30. 38 Fed. Reg. 24778 (1973).

31. *Jacobellis v. Ohio*, 378 U.S. 184, 197 (1964) (Stewart, J., concurring).

32. Presidential Message No. 182, 95th Cong., 2d Sess., 124 Cong. Rec. S8679, S8680 (daily ed. June 7, 1978).

33. Alaska Stat. §46.03.758 (Supp. 1977). *See* text *supra* at §III.A.2.a.

34. Pub. L. No. 94-265, 90 Stat. 331, 16 U.S.C.A. §§1801 *et seq*. (West Supp. 1977).

35. *See, e.g., Tumey v. Ohio*, 273 U.S. 510 (1927).

36. 33 U.S.C. §901 *et seq*. (1970). The schedule of disability compensation under the LHWCA appears at 33 U.S.C. §908 (1970).

37. See generally A. Larson, Workmen's Compensation §58 (desk ed. 1972).

38. See Letter from Donald L. McKernan, Chmn., Nat'l Advisory Comm. on Oceans and Atmosphere, to Sen. Edmund S. Muskie, June 6, 1978.

APPENDIX A

Fidell and Du Bey, "Proposals for Reform in the Assessment of Oil Spill Damages," before American Institute of Biological Sciences, Conference on Assessment of Ecological Impacts of Oil Spills (June 1978) [Steven Helgeson, Legal Intern, assisted in the preparation of these materials].

Federal Laws
Relevant to Oil Spill Damage Assessment

Applicable Federal Law	Prohibited Acts	Geographical Jurisdiction	Extent of Liability	Legal Defenses to Liability	Legal Damages (Costs) Recovered	Fines and Penalties Available	Availability of Fund: Size and How Financed	Recovery Upon the Fund	Preemption of ·eral or State
·ivers and Harbors Act ·f 1899 (Refuse Act) ·33 USC §§407, 411)	Discharge from vessel or shore of any refuse water including commercially valuable oil §407	Tributaries of navigable waters and banks of navigable waters §407	See Fines and Penalties Vessels are liable <u>in rem</u>	Compliance with permit §411	None	$500 - $2,500 or imprisonment for not more than one (1) year or both §411	None	None	None
·ederal Water Pollution ·ontrol Act Amendments ·f 1977 (FWPCA) ·33 USC §1321)	Discharge of oil or hazardous substances in harmful quantities (visible sheen) §1321(b)(1)	Waters of the U.S. including the territorial sea, adjoining shoreline and contiguous zone...or in connection w/activities under OCSLA or DWPA of 1974, or which may effect natural resources appertaining to management authority of U.S. (Fisheries Conservation and Management Act 1976)	§1321(f) <u>Inland oil barge</u> - <u>$125 per gross ton</u> or $125,000 whichever is greater <u>Any other vessel</u> - <u>$150 per gross ton</u> (or, for a vessel carrying oil or hazardous substance as cargo, $250,000) whichever is greater facility - up to $50,000,000 Where willful negligence or willful misconduct the spiller liable for total cleanup cost	1) Act of God 2) Act of war 3) Negligence of U.S. 4) Act or omission of third party Spiller entitled by subrogation to all rights of U.S. to recover from third party... In addition... provisions shall not apply in case where liability established pursuant to OCSLA or DWPA of 74'	Actual cost of removal incurred by the U.S. <u>including</u> the cost of restoration or replacement of natural resources. §1321(f)	<u>Failure to notify</u> up to $10,000 or one (1) year imprisonment or both 1321(b)(5) <u>Failure to comply with regulations</u> up to $5,000 for each violation §1321(i)(2)	Maintained at $35,000,000 financed by recovery from spiller for costs of removal §1321(k)	Available to Federal agencies for cleanup operations §1321(l)	None, also does not preempt liability under OCSLA or DWPA of 1974 §1321(o)
FWPCA (33 USC §§1311, 1342)	Discharge of any pollutant by any person §1311	Waters of the U.S. including the territorial sea §1362	See Fines and Penalties	Compliance with permit §§1311, 1319	None	Criminal - $2,500 -$25,000 per day of violation or imprisonment for not more than one (1) year, or both Additional fines for subsequent offenses up to $50,000 per day or two (2) years or both. <u>Civil Penalty</u> - up to $10,000 per day of violation. <u>False Statement</u> - fine of $10,000 or six (6) months, [illegible] both. Additional noncompliance fe[illegible] equal to the economic value of a delay in compliance §1319	None	None	None so long as state actions are as stringent as Federal requirements

Federal Laws
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Trans-Alaska Pipeline Authorization Act (43 USC §1651 et seq.)	Pollution along or in vicinity of pipeline right-of-way; discharges from vessels loaded at Valdez	Covers the movement of Alaskan crude oil from the TAP to any U.S. port	Holders of right-of-way: limited to $50,000,000 for any one incident. Vessels: limited to first $14,000,000 per incident	1) Act of war 2) Negligence of U.S.	All damages (including cleanup costs) public or private, sustained by any person or entity, including resident of Canada. §1653 (d) "Damage" or "damages" means any economic loss, arising out of or directly resulting from an incident, including but not limited to: 1) Removal costs. 2) Injury to, or destruction of real or personal property. 3) Loss of use of real or personal property. 4) Injury to, or destruction of natural resources. 5) Loss of use of natural resources. 6) Loss of profits or impairment of earning capacity due to injury or destruction of real or personal property or natural resources, including loss of subsistence hunting, fishing and gathering opportunities. 7) Loss of tax revenue for a period of one year due to injury to real or personal property. 43CFR 29.1(d)	None. (Stipulation §25 provides for temporary suspension of operations to protect either public health or the environment	Size limited to $100,000,000. Financed by 5¢ per barrel of oil loaded on a vessel at Valdez	Applies only to damage caused by vessel discharges. Available for claims exceeding $14,000,000 up to $100,000,000	None, (however, no multiple recovery for same injury)
	§1653					Stipulation §25-Civil	§1653(c)	§1653(c)	§1653(c)
Deepwater Port Act of 1974 (33 USC §1501 et seq.)	Discharge of oil in marine environment from a vessel which has received oil and discharges of oil from the port itself	The marine environment within any safety zone established around a deepwater port.	Vessel: up to $150 per gross ton or $120,000,000 whichever is less (vessel is liable in rem) §1514(e) Deepwater Port: up to $50,000,000 Gross negligence or willful misconduct will make spillers liable for full amount of all cleanup costs §1517(e)	1) Act of war 2) Negligence on part of U.S. 3) Caused by actions of 3rd parties	All damages to real or personal property sustained by any person including cleanup costs. Damages includes injury to natural resources of marine or coastal environment.	Willful violation: up to $25,000 per day or one (1) year or both. Failure to notify up to $10,000 or one (1) year or both.	Size limited to $100,000,000 financed by 2¢ per barrel on oil either loaded or unloaded at deepwater port. Exception - Alaskan oil	Applies to all damages and cleanup costs in excess of those compensated by spiller	None (however, no multiple recovery for same injury.
	§1517	§§1508,1517		§1517(g)	§1517	§1517(b)	§1517(f)	§1517(f)	§1517(k)

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Applicable Federal Law	Prohibited Acts	Geographical Jurisdiction	Extent of Liability	Legal Defenses to Liability	Legal Damages (Costs) Recovered	Fines and Penalties Available	Availability of Fund: Size and How Financed	Recovery Upon the Fund	Preemption of [Fed]eral or State
Outer Continental Shelf Lands Act 43 USC 1331 et. seq.	The lessee shall not pollute land or water or damage the aquatic life of the sea or allow extraneous matter to enter and damage any mineral or water-bearing formation. All spills or leakage of oil or waste materials of a size or quantity specified by the designee under the pollution contingency plan shall also be reported by the lessee without delay to such designee. 30CFR 250.43	All submerged lands lying seaward and outside of a line three geographical miles distant from the coast line of each State (three marine leagues for Texas and Florida) Sec. 1332, 1301	If the waters of the sea are polluted by the drilling or production operations conducted by or on behalf of the lessee, and such pollution damages or threatens to damage aquatic life, wildlife, or public or private property, the control and total removal of the pollutant, wheresoever found, proximately resulting therefrom shall be at the expense of the lessee. The lessee's liability to third parties, other than for cleaning up the pollutant shall be governed by applicable law. 30CFR 250.43	Applicable State and Federal law 30CFR 250.43	Control and removal of pollutant, damages - other applicable law 30CFR 250.43	None	None	None	-(2) To the extent that they are applicable and not inconsistent with this subchapter or with other Federal laws...the civil and criminal laws of each adjacent State as of August 7, 1953 are declared to be the law of the United States for that portion of the subsoil and seabed of the outer Continental Shelf, and artificial islands and fixed structures erected thereon, which would be within the area of the State if its boundaries were extended seaward to the outer margin of the outer Continental Shelf. -Sec. 1333

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Proposed Federal Laws
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Applicable Federal Law	Prohibited Acts	Geographical Jurisdiction	Extent of Liability	Legal Defenses to Liability	Legal Damages (Costs) Recovered	Fines and Penalties Available	Availability of Fund: Size and How Financed	Recovery Upon the Fund	Preemption of Federal or State Law
National Oil Pollution Liability and Compensation Act of 1977, S.687, 95th Cong., 1st Sess.	Discharge of oil §3(g)	Waters of the U.S., including the territorial sea and the OCS and including the fishery resources of the fishery conservation zone §§2(a)(1), 3(12), 3(13) & 3(14).	Vessels carrying oil in bulk- $300 per gross ton or $30,000,000 whichever is less. Facility-up to $100,000,000 spiller is liable for full amount of damages and cleanup costs where such discharge was the result of gross negligence, willful misconduct or a violation of applicable safety standards §5	1) Act of war 2) Negligence or willful act of claimant 3) Act or omission of third party 4) Act of God 5(d)	Cleanup costs and damage to or cost of restoring, repairing, or replacing any real or personal property, lost income due to damage to property including natural resources. Up to one (1) year loss of federal, state or local government tax, royalty, rented or net profit share revenue. §§6,10	Civil-up to $10,000 for failure to pay oil facility fee into fund. §4(b)(2),(c)	Size limited to $200,000,000. Financed by a fee up to 3 cents per barrel collected from facility owners when oil is loaded or unloaded §§4(b),4(b)(3)	All damages and cleanup costs not compensated by spiller. Except where damage was caused solely by claimant's own negligence or willful act. §5(a)(b)(c)	State Law- §9(e) Vessel and facility financial responsibility provisions are preempted. No other state preemption. Federal Law- Where conflict or inconsistency this act preempts other federal law. (No multiple recovery for same injury.) §17(a)&(b)
Senate Bill 9 OCSLAA 1977 Title IV - Fishermen Contingency Fund [see also page 5 infra]	Damage to commercial fishermen vessels and fear	Outer Continental shelf	Full	None	Damages and loss to profits to commercial fishing vessels and gear -replacement valve as a result of oil and gas exploration, development, or production on OCS; loss of revenue	None	Fee not to exceed 1¢ per barrel of oil obtained from OCS Size - not less than 2,000,000 and not more than 5,000,000 -those causing damage reimburse the Fund	Fisherman's Claims Board recommendation sue or be sued in own name	None

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-nate Bill 9: Outer ntinental Shelf Lands -t Acendments of 1977 itle III - Offshore ilspill Pollution Fund -ee also Page 4, <u>supra</u>)	Discharge of oil from any offshore facility located on the outer continental shelf or from vessel, (visible sheen). (vessel-operating above OCS or transporting oil from offshore facility) -Sec. 303	All submerged lands lying seaward and outside of area of lands beneath navigable waters as defined in Section 1301 (3 geographical miles seaward of coastline) -Sec 301	Liability for all cleanup cost incurred <u>vessel</u> - damages up to $150 per gross registered ton <u>Facility</u> - damages up to $35,000,000. Except where gross negligence or willful misconduct, or a result of violation of applicable safety, construction, or operating standards or regulations, then liable for full amount of damages. -Sec. 308	1) Act of war 2) Negligence or intentional act of the damaged party or any third party (including any governmental entity Sec. 308	1) cleanup costs to govt. entity including measures taken to mitigate damages to public 2) cost to person for any loss or injury w/respect to any real or personal property damaged or destroyed; 3) cost to owner of restoration, repair or replacement of any real or personal property, and any income necessarily lost by owner during restoration, repairing or replacement, and cost of any reduction in value 4) any loss of income or impairment of earning capacity for a period not to exceed 5 yrs due to damages to real or personal property, or to natural resources, w/o regard to ownership (claimant must derive at least 25% of earnings from activities which utilize such property or natural resources) 5) any costs and expenses incurred by Fed. govt. or any State govt. in the restoration, repair, or replacement of natural resources 6) any loss of tax revenue by govt. enity for period not to exceed 1 yr. due to injury to real or personal property. -Section 307	Failure to notify - up to $10,000, or imprisonment for not more than one yr, or both - Section 304 Failure to comply w/provisions regulations, or orders issued under the Act after notice - civil penalty not more than 10,000 per day continuance of failure Knowingly and willfully violates provisions regulations, or orders designed to protect health, safety or the environment or conserve natural resources - upon conviction be punished by a fine not more than $100,000 or imprisonment for not more than 10 years, or both (each day a seperate violation) -Section 24	Maintained at a level not less than $100,000,000 and not more than $200,000,000 Financed by a fee not to exceed 3¢ per barrel on oil obtained from OCS which is imposed upon owner of oil, also by sums received through reimbursements, fines, penalties, investments, and judgments. Section 310	Cleanup costs and Damages not compensated pursuant to Section 308 (damages in excess of those compensated by spiller) -Section 309	Except as provided does not preempt the field of liability or to preclude any state from imposing additional requirements or liability for any discharge resulting in damage or cleanup costs w/in the jurisdiction of any state. -compensation pursuant to this title shall preclude recovering compensation for some damages or cleanup costs pursuant to any other Fed. or State law. -Section 322 Jurisdiction does not include vessels or deepwater ports as defined by the Deepwater Port Act of 1974 (33 USC 1502)

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..l Pollution Liability . Compensation Act of 1977 Senate Bill S.2083 ..5th Cong. 1st Sess.	Discharge of oil in harmful amount	U.S. navigable waters, contiguous zone; outside territorial limits when in connection w/OCSLA or Deepwater Port Act activities causing injury to U.S. resources - Sec 3	<u>Vessel</u> which does not carry oil in bulk - $150 per gross ton <u>Vessel</u> which carries oil in bulk $500,000 or $300 per gross ton, whichever is greater <u>Facility</u> - $50,000,000 or lesser amount as established for classes of facilities deepwater ports & offshore oil production Facilities - $50,000,000 Complete *liability* for gross negligence or willful misconduct; gross or willful violation of applicable safety, construction or operating standards, or regulations - Sec. 6	- act of war - natural phenomenon of an exceptional, inevitable, and irresistable character - act of third person - Sec. 6	-value of loss of real or personal property -loss of use of real or personal property -loss of any natural resources -loss of income or impairment of earning capacity -loss of tax, royalty, rental, net profits by govt. enity not to exceed 1 yr. -Sec 7	-failure to provide for financial responsibility - civil penalty not to exceed $10,000 -failure to notify - upon conviction fine not to exceed $10,000, or imprisonment for not more than one year or both -failure to collect or pay fund fee civil penalty not to exceed $10,000, amt. due fund w/ interest Sec. 16, Sec 5	financed by fee not to exceed 3¢ per barrel levied at refinery and terminal for export or entry -monies reimbursed to fund -criminal & civil penalties maintained at $200,000,000 Sec. 5	to extent not otherwise compensated Sec. 6	shall not preempt State from imposing liability for damages and cleanup -recovery under Fund precludes recovery under other law -supersedes all other conflicting or inconsistent Federal laws -conforming amendments to Trans-Alaska Pipeline Act, OCSLA, DWPA, WPCA Sec. 18, Sec. 19
..mestic Oil Pollution Liability, Compensation, and Fund - H.R. 6803, 1977 - 95th Cong. 1st Sess.	Oil pollution in unlawful quantities -Sec. 103, 101	U.S. navigable waters, contiguous zone; outside territorial limits when in connection w/OCSLA or Deepwater Port Act activities causing injury to U.S. resources Sec. 101	-<u>Vessel</u> other than a ship or other than an inland oil barge - (not carrying oil in bulk) $150 per gross ton -<u>Inland oil barge</u> - $150,000 or $150 per gross ton, whichever greater -<u>ship</u> (vessel carrying oil in bulk) - $250,000 or $300 per gross ton, whichever greater up to $30,000,000 -<u>OCSLA offshore facility</u> - total removal costs plus $50,000,000; -<u>other facility</u> - $50,000,000 or lesser amount as established by the Sec. for various classes full recovery - gross negligence or willful misconduct; or violation of applicable safety, construction, or operating standards -Sec. 104	Except as to removal costs, no liability where due to: -Act of war -3d persons Sec. 104	Removal costs Injury to real or personal property injury or destruction of natural resources loss of use of natural resources loss profits or impairment of earning capacity loss of tax revenue for period of one yr. -Sec. 103	-failure to collect fund fees - civil penalty not to exceed $10,000 -failure to comply w/financial respon. provisions - civil penalty not to exceed $10,000 -failure of notification - upon conviction. not to exeed $10,000 or imprisonment for not more than 1 yr., or both -Sec. 111, 102	Fee from owners of refineries receiving crude oil, and from owners of terminals receiving oil for export or import not to exceed 3¢ per barrel - Sec. 102 -reimbursement to fund - Sec. 108 -Size - not less than $150,000,000 and not more than $200,000,000 -Sec 102	To extent not otherwise compensated - Sec. 104 - Sec. 107	To extent in conflict or otherwise inconsistent w/any other provisions of law relating to liability or limitation thereof, the Act supersedes all other - Sec. 104 -states may impose tax or fee for cleanup & removal operations - Sec 110 -Alaska Pipeline, FWPCA, DWPA, amended to place under Act - Sec. 201

ECONOMIC VALUES AND ECOLOGIC IMPACTS ASSOCIATED WITH OIL SPILLS

by

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ECONOMIC VALUES AND ECOLOGIC IMPACTS ASSOCIATED WITH OIL SPILLS[1]

Elizabeth A. Wilman
Resources for the Future

The coastal and marine resources of the nation are increasingly the focus of conflicting demands. In order to make rational decisions with respect to the allocation of these resources, we need to have some assessment of the economic value losses and gains associated with changing patterns of use. This paper discusses a study under way which seeks to estimate such values in the case of environmental impacts affecting beaches in a tourist oriented economy.

The Problem

The coastal and marine resources of this nation have become the focus of an increasingly growing and varied set of demands. The growth of diverse demands, in a situation where many of the services provided are not valued--or are not correctly valued--by the private market, has inevitably resulted in growing conflict among uses and over the priorities of coastal and marine resource management. The conflicts are very evident and a few have gone as far as the United States Supreme Court. The conflict over the State of Washington's Tanker Law, an attempt to put restrictions on tanker traffic in Puget Sound, is a case in point (Ray v. Atlantic Richfield).[2] The challenges to the United Department of Interior's sale of oil and gas leases in the Outer Continental Shelf (OCS) are others (County of Suffolk v. Secretary of Interior) (Massachusetts v. Andrus).[3] State coastal zone management plans, which ideally are intended as vehicles to resolve some of these conflicts, have themselves been the focus of conflict. In the fall of 1977, companies involved in the development of oil and gas resources sought to enjoin the National Oceanic and Atmospheric Administration (NOAA) from approving the proposed California Coastal Zone Management Plan (American Petroleum Institute v. Knecht, 1977.)[4] The suit challenged that the California Plan did not provide clearly for the offshore siting of energy related facilities of regional and national importance. Most recently approval of the Massachusetts Coastal Zone Management Program was similarly enjoined (American Petroleum Institute v. Knecht, 1978).[5] In addition, as states use more and more regulations and permits to influence the amounts and types of private market resource uses that will occur in coastal areas, the

inevitable conflicts between resource managers and private owners are also increasing. The "taking issue" is becoming a focal point of such disputes (CEEED v. California Coastal Commission) (County of Carteret v. Coastal Resources Commission).

It may be argued that as legal precedents are established; as new legislation, such as the pending OCS Lands Act amendments (S. 9) (H. R. 1614)[6] and the proposed tanker regulations and oil spill liability program (S. 682) (H.R. 6803), comes into force; and as state coastal zone management programs come to maturity; such conflicts will be resolved.

To some extent this may occur. Imposing an oil spill liability program and separation of the exploration and production leasing decisions in order to allow reconsideration in light of new information would appear to be steps in the right direction. However, overall the nature of the emerging legal framework for deciding coastal and marine resource issues does not indicate a very clear picture of the pattern of resource allocation to be expected and, of whether economic welfare will be better under that allocation or another. It leaves unanswered the question of how individual preferences for salt marshes versus housing developments, or for offshore oil and gas versus pristine beaches, will be registered or measured. Except for the political process, itself fraught with unknowns, there does not seem to be any systematic approach to the evaluation of alternative uses of coastal and marine resources.

Economic Values and Ecological Impacts

The concept of economic value is itself an item of invaluable aid in the evaluation of the ecological impacts of oil spills, as well as of any other perturbation that can influence or be influenced by the decisions of human beings, individually or collectively.

For many goods traded in the private market system, price is an accurate measure of economic value. Unfortunately, due to the common property and/or public good character of many of the services provided by coastal and marine resource systems, these services--although they do have economic value--do not necessarily have prices which accurately reflect this value.

In order to make management decisions affecting coastal and marine resource uses, we need to obtain reasonable proxy measures for the economic values associated with changes in service flows from coastal and marine resources. The next section of this paper discusses a case study designed for the measurement of the economic value associated with environmental impacts that can alter the services that beaches, such as those in the Cape Cod area of Massachusetts, supply to tourists who visit the area.

Beach Recreational Values--One Approach

Introduction

The Cape Cod area of New England supports a substantial recreation and tourist-oriented service industry. This is partially the result of its accessibility to many urban centers of the northeastern United States. However, it is also partially due to the aesthetic and recreational attractiveness of the natural environment, in particular the beaches. Oil spillage from OCS exploration and development, pipelines or tanker traffic, which comes ashore on these beaches would, to some extent and for some time, alter the ability of these resources to provide the services which are part of the package the tourist industry sells to its clients. What is proposed here is to examine the market for tourist accommodations and to determine how the actual or imputed rental value for these accommodations varies with beach accessibility and quality; and how closure or quality deterioration of various beaches due to oil spillage would alter these values.

The Conceptual Model

The model used here is the hedonic pricing model. A good discussion of it can be found in Rosen (1974). The concept, as applied here, suggests that when an individual purchases (rents) tourist accommodations, what he is buying (renting) is not just the accomodations themselves, but rather *a bundle or package of characteristics, which includes the characteristics* of the unit itself, of the establishment of which the unit is a part, and of the environmental services to which the individual gains access. Virtually all tourist accommodations on Cape Cod are selling, among other things, proximity to beaches of varying qualities. Accomodations vary not only with respect to the size of the unit and whether or not they have air conditioning, etc., but also with respect to how accessible beaches are to the users of these accommodations, and with respect to the quality of these beaches. Implicit in the model are the following assumptions:

a. that the Cape Cod-Martha's Vineyard area describes a market for tourist accommodations, within which there is a wide array of bundles, with varying amounts of the characteristics, available from which to choose,

b. that all consumers in the market accurately perceive the characteristics available in each bundle,

c. that the market is in a short-run equilibrium,

d. that variation in the amounts of the characteristics offered by different tourist accommodation bundles, is fully accounted for by variation in the prices (rents) charged for these accommodations, rather than also being reflected in the prices of related services such as restaurants.

e. that variation in the amounts of the characteristics in the tourist accommodation bundle *affects only the satisfaction* the individual gets from the consumption of that bundle, and does not affect the satisfaction he gets from other bundles he may consume in the form of automobiles, overcoats, golf clubs, or whatever.

The first step is to specify an hedonic function, such that the price of the bundle is function of the amounts of the characteristics contained in that bundle. Equation [1] below is an example of an hedonic function that could be statistically estimated from a set of observations on the prices of tourists accommodations, and amounts of the various characteristics present in each bundle.

$$[1] \quad P_r = F(C_1, C_2, C_3, --- C_n)$$

where: P_r is the price of the package

C_i is the amount of the ith characteristic

The hedonic prices for each characteristic in the bundle can then be calculated. The first partial derivative of P_r with respect to C_i gives the hedonic price for C_i. If C_1 is beach quality and C_2 is beach accessibility, then $P_1 = \frac{\delta P_r}{\delta C_1}$ is the hedonic price for beach quality and and $P_2 = \frac{\delta P_r}{\delta C_2}$ *is the hedonic* price for beach accessability.

Once these equilibrium prices have been determined, then the question becomes whether or not one can derive the demand curves for beach quality and accessibility from these prices. Let us examine, for example, the market for beach quality C_1, where [2] represents the demand curve for beach quality, and [3] the supply curve.

$$[2] \quad P_1 = C(C_1, C_2 --- C_n, Y_1)$$

$$[3] \quad P_1 = L(C_1, C_2, --- C_n, Y_2)$$

where Y_1 represents socioeconomic variables that act as demand curve shifters

Y_2 represents background variables that act as supply curve shifters.

The first essential condition needed in order for it to be possible to estimate the demand curve is that there be some variation in P_1 (that is $\frac{\delta P_r}{\delta C_1} \neq$ constant). What this means is that repackaging is not possible,

or that two porches on one cottage is not the same as two porches, one on each of two cottages. This is a necessary, though not sufficient, condition for identification of the demand curve. If, in addition, we have a condition such as identical preferences for consumers of the accommodations then the demand curve can be identified. This assumption has been used by researchers such as Brown (1977). This is, however, an unusually strong assumption. Alternatively we could assume that the supply of C_1 was independent of P_1 (i.e., $C_1 = X$ rather than [3]). Harrison and Rubinfeld (1978) have used this assumption. In this manner the demand curve can be identified but this still may be a stronger assumption than is reasonable in the case of beach quality.

For any one bundle, the quality of the attendent beach facilities may well be a function of its price. That is local entrepreneurs knowing that their units will rent for higher prices if the associated beaches are clean and litter free, may be induced to undertake or to seek clean-up activities. A more realistic model requires a supply function which incorporates both a price-dependent aspect of beach qaulity supply and an independent or exogeneous aspect. Using a simple linear model where the amounts of characteristics other the C_1 are assumed not to affect the demand or supply curve for C_1, we could have the following structural equation

[4] $P_1 = aC_1 + bM$ (demand curve)

[5] $C_1 = dP_1 + eE$ (supply curve)

where M = an exogenous demand shifter (income level)

E = an exogenous supply shifter (environmental conditions beyond the control of the market)

The reduced form equations here would be

[6] $P_1 = \dfrac{aeE}{1-ad} + \dfrac{bM}{1-ad}$

[7] $C_1 = \dfrac{bdM}{1-ad} + \dfrac{eE}{1-ad}$

and the reduced form coefficients are such as to allow the structural coefficients to be exactly identified. Thus, the demand curve in [4] can be identified, and consumers' surplus measured. In this case the supply curve can also be identified and the producers' suplus measured.[7] This is important because in this case there is a cost to the supplier of supplying beach quality.

If [4] had not included the exogenous shifter M, only the demand curve could have been identified. No measure of producer surplus or rents could have been made unless the supply curve was independent of P_1.

Small changes in beach quality from changes such as oil spills are represented by changes in E. Before any change E the value of beach quality is

$$[8] \quad V = \int_0^{C_e} \left(aC_1 + bM - \frac{1}{d} C_1 + \frac{eE}{d} \right) dC_1 = \quad \text{where } C_e \text{ is the equilibrium quantity}$$

$$\left(a - \frac{1}{d} \right) \frac{C_e^2}{2} + bMC_e + \frac{e}{d} EC_e$$

Differentiating [7] and [8] with respect to E we get

$$[9] \quad \frac{\delta P_1}{\delta E} = \frac{ae}{1 - ad}$$

$$[10] \quad \frac{\delta C_1}{\delta E} = \frac{e}{1 - ad}$$

Given the change in E the new value is

$$[11] \quad V' = \int_0^{C_e + \frac{e}{2 - ad}} \left(aC_1 + bM - \frac{1}{d} C_1 + \frac{e}{d} E + \frac{e}{d} \right) dC_1$$

To find the net loss from the small change in E we subtract V' from

$$[12] \quad \text{Loss} = \frac{e}{d} \left(C_e + \frac{e}{2\,(1 - ad)} \right)$$

So far, we have discussed this problem in terms of reduction in beach quality, given the same level of all other characteristics including accessibility. However, accessibility may vary. If, for example, a beach is closed, then it is no longer accessible. The accessibility variable C_2, which may be measured in terms of "distance to nearest available beach," will experience a small change and we have an analysis similar to that above. However, in this case, we may be able to assume legitimately that the supply of C_2 is independent of P_2.

Data and Analysis

The first step in the analysis is to estimate equation [1]. From this equation the implicit prices of the characteristics may be determined. The

second step is to use these prices to estimate the demand curve for the characteristic of concern. The data required for the estimation of equation [1] include the implicit or actual rental price of summer homes and tourist accommodations and information on all of the relevant characteristics including beach quality and accessibility. There may, in fact, be several dimesions to beach quality including size, sand texture, sand cleanliness, intensity of use, attractiveness of nearby buildings (if any) and attrativeness of nearby vegetation. In estimating equation [1] it would be useful to look at these characteristics for (1) the closest beach, and (2) averaged over the beaches within roughly a five minute driving time from the hotel or cottage. Accessibility variables must be included also. Here again, we could use (1) the distance to the closest beach, and (2) the average distance of beaches within five minutes drive.

The second stage uses the P_i's derived from [1] to estimate demand (and sometimes supply) relationships. If we have the situation, as in [5], where the supply of the characteristic is dependent on its price, then we do need both consumers' and producers' surpluses. Equation [5], however, involves somewhat difficult measurement problems. This is due to the fact that there are two measures, C_1 and E, both involving the same beach quality characteristic. The measure C_1 measures that characteristic, including both the amount of it due to natural factors and that due to the efforts of the supplier of the bundle. Beach cleanliness is an example of a characteristic which might have both independent and price-dependent components. This means C_1 is the overall measure of beach quality, and E_1 is beach quality resulting from price independent (i.e. natural) causes.

Much of the necessary data will be obtained from the Cape Cod Chamber of Commerce and from real estate agents around the Cape. Information to be collected will include data on seasonal rental rates (in the case of nonrented second homes--potential rental rates), the capacity of the establishment and seasonal occupancy rates. It would include a checklist for the in-house quality of the accommodations (i.e., unit size, air conditioning, color TV, etc.), and information on the distance to the nearest beach and on the average distance to the group of beaches within roughly a five minute drive. Where necessary, information available from the Chamber of Commerce and from real estate agents will be supplemented by interviews with the owners or managers of the accommodations themselves.

Information on beaches and their characteristics is also required. The first step is the determination of the set of relevant characteristics. This step is currently underway. Meetings were called with Conservation Commissioners and Beach Committee members from the towns around the Cape (and including Martha's Vineyard), in order to explain the purpose of the study and the type of information we were seeking. Questionnaires were mailed out to the individuals who attended the meetings. Respondents were asked to consider the beaches they knew best in their area of the Cape and to list the factors that they perceived were most important in attracting tourists to these beaches. They were also asked to list the factors that repelled tourists from beaches and to rank the factors they listed in order of perceived importance.

Partial returns on this questionnaire to date, indicate that the following factors may be important.

1. beach material--fine sand, stony, mud
2. water-calm vs. heavy surf
3. availability of fishing and shellfishing
4. presence or absence of noxious insects
5. beach gradient--flat vs. steep beach
6. water temperature
7. cleanliness of facilities
8. adequacy of parking
9. presence or absence of seaweed
10. expectation of whether or not the beach will crowded
11. cleanliness of beach and water

After the relevant characteristics are determined they will be measured. Data collected by the Massachusetts Coastal Zone Program, and anlysis of low altitude aerial photography of the beaches will be used. Finally some characteristics may require measurement (or verification) by on-site ratings. It is likely, of course, that the total number of characteristics determined at this stage will be too large to deal with in a regression model. It will be necessary to narrow down the number of characteristics by performing factor analysis prior to the regression analysis.

Information on the socioeconomic characteristics of consumers of the tourist accommodations also will be collected. The most important socioeconomic factor influencing demand is probably income level.[8] This will be obtained by collecting a sample of home addresses of different types of tourists in different areas from such records as hotel room registrations. The model and year of car the tourist drives may be used as a proxy for income level, if available. In addition addresses may be used to match up with block statistics for SMSA's (U.S. Department of Commerce, Bureau of Census 1971) in order to estimate of the average value of housing units for the block in which the tourist lives. This, too, can be used as a proxy for income.

The purpose behind this methodology is to put an economic value on changes in the beach quality, available to tourists using overnight (or longer) accommodations, resulting from environmental impacts such as oil spillage on these beaches.

The approach suggested here attempts to do this by looking at existing quality variation cross-sectionally over Cape Cod and Martha's Vineyard beaches. When we introduce an exogenous perturbation such as an oil spill into this system, there are a few concerns to which close attention must be paid.

First, it must be true that the oil spillage can be represented by a change in the supply of a beach quality characteristic such as beach cleanliness, which matters in the hedonic equation. There are two possible problems. Although there may be a characteristic in terms of which the perturbation could be measured, there currently may not be enough variation cross-sectionally to allow this characteristic to be significant in the hedonic equation. In this case nothing can be said about the economic

value of the change in beach quality caused by an oil spill, because the data are not sufficient to show it. The second problem that could arise is that although there may be a characteristic in terms of which the perturbation can be measured, and although there may be plenty of cross-sectional variation with respect to this characteristic, the price variation may be so strongly dominated by other factors that no significant relationship with the relevant beach quality characteristic can be found.

If it can, in fact, be shown that a variable such as "beach cleanliness" has a significant effect on prices charged for tourist accommodations, then it is also true that our ability to identify a demand curve for beach cleanliness and to estimate the economic value of a marginal loss in beach cleanliness depends upon some crucial assumptions. First, we have the identification assumptions. In all likelyhood these will represent an oversimplification of reality. For example, it would be useful to assume that the supply of beach cleanliness is unaffected by its price: This may not be absolutely true but it may be acceptable, although it is incumbent upon the researcher to show either that the limiting assumptions of the model do not matter, or to show how sensitive the estimates are to alteration of the crucial assumptions.

In addition to the identification assumptions there are some assumptions necessary in order to use the model and the demand curve for beach cleanliness to estimate the change in value associated with a change in "beach cleanliness." To estimate the change in value we must assume that everything else (except beach cleanliness) is held constant. This includes all other characteristics and their prices, and the net income of consumers. Even if these assumptions hold, the estimate of the change in value is not an exact one, as no economic actor is allowed to adjust to changes in the environment. Basically, this means that the method is most useful for measuring small (or marginal) changes, rather than large (or non-marginal) changes.

Uncertainty

Although there may be considerable uncertainty in the economic value estimates themselves, it must also be remembered that to make meaningful estimates of the economic values associated with er ironmental perturbations, physical, chemical, biological and/or ecological models may have to be applied and interfaced with each other and with the economic model, and that there will be uncertainty involved in the results these models produce as well.

In the case of oil spillage on beaches from OCS oil and gas activities, there are models that predict probability of spillage from wells with various production profiles, and from the pipelines, ships or barges that transport it to shore (Stewart 1975). There are models that look at what happens to the oil after it is spilled (Smith et al., 1976). Where does it go, how quickly, and what happens to it along the way? There are, of course, many variables where uncertainty may enter. There are many different kinds of oil, which may evaporate, degrade, disperse, float or sink. Existing modelling

efforts are better at dealing with some of these eventualities than others. Surface movements of oil can be modelled fairly well given data on current and wind conditions. Evaporation and dispersion can also be analyzed. However, if oil sinks, becomes suspended in the water column or buried in the sediments, its fate is more uncertain. Evidence suggests that in the latter case, it may take considerably longer to degrade (Blumer and Sass 1973). The effect oil spillage has on a beach is influenced by what has happened to it before it gets there. The effect of tar balls or small well weathered oil globules coming ashore over an extended period of time and space, will be different from a slick of fresh oil washing up in one location, although the amount of oil originally spilled may be the same.

The season of the year in which oil impinges on the beach is also important in determining economic values. So far as tourists are concerned the season during which the beach is degraded may be very important. The availability of clean-up technology to reduce the duration of at least the most visible aspects of the spill, may well reduce the loss in economic value associated with the spill.

Given all the various sources of uncertainty that arise in making estimates of the economic value of the loss in beach services to tourists, it is quite clear that the bottom line estimates must be used by decision makers, with an awareness of the extent of the uncertainty and with a strategy for coping with this uncertainty in the decision framwork.

In this respect a couple of items might be noted. First of all, the decision maker's attitude toward risk will influence how he incorporates uncertainty into the decision framework (Dorfman 1962) (Menger 1968). If the decision maker is risk neutral, expected values will be used in the decision analysis. If the decision maker is extremely risk averse, the minimax criterion will more closely describe how risk affects his decisions. Using minimax the decision maker will try to maximize his minimum gain, or miminize his maximum loss. Given identical information with respect to a set of alternative actions, decision makers who vary with respect to their attitudes toward risk may make different decisions.

Consider two alternative actions A and B, both having certain benefits of \$100. However their costs are presumed to include some environmental damages of uncertain magnitude. In the case of action A there is a 0.5 probability that state of the world X will occur and that there will be damages of \$45. On the other hand, there is a 0.5 probability that state of the world Y will occur and that there will be damages of \$55. In the case of action B, the damage that will be associated with state of the world X is \$90 and with state of the world Y, \$0. The risk neutral decision maker will view the cost of project A as being 0.5 (45) + 0.5 (55) = \$50 and the cost of project B as 0.5 (90) + 0.5 (0) = \$45. He will choose project B because it has a greater expected value of net benefits. However, the extremely risk averse decision maker would observe that the worst he could do with project A would be 100-55 = \$45 and the worst he could do with project B would be 100-90 = \$10. He would maximize his minimum gain by choosing project A.

It is also worth noting that when uncertainty prevails and there are large costs involved in taking the exposte "wrong" decision, it may be better to postpone the choice of such potentially costly alternatives and to make investments in information which will reduce uncertainty (Arrow and Fisher 1974) (Henry 1974).

Suppose, for example, that by making a $10 investment in information we can know at some reasonable time in the future (roughly 10 years) whether the low or high damage situations will occur. Postponing the decision for 10 years would enable the decision maker to make his choice between A and B somewhat differently. If state of the world X is determined to be the one which will occur, then action A would be choosen; if state of the world Y is determined to be the one which will occur, then B would be chosen. Viewing the situation from the perspective of the present and assuming a zero discount rate (for convenience), the net benefits perceived by the risk neutral decision maker are 100-10-(.5 (45) + .5 (0)) = $67.50. The investment in information is definitely a worthwhile strategy. In fact an investment of up to $17.50 would be worthwhile. The extremely risk averse decision maker would view the situation somewhat differently. He would perceive that the worst he could do with this strategy would be 100 - 10 - 45 = $45. A $10 investment makes him indifferent between the investment strategy, and simply going ahead with project A now. The investment would have to be less than $10 for this strategy, in order to make it preferable to simply proceeding with A.

In both the examples we have illustrated above, it was true that some investment in information could increase our net benefits. This does not imply that investments in data collection or modelling efforts should be undertaken indiscriminantly. Instead some of our uncertainty could be removed by judicious investments in order to extend modelling efforts, and in order to collect data that will give us better estimates of the parameters of these models. In the former case, it would be useful to test the sensitivity of results to variation in the assumptions of the model as well to examine alternate more generalized formulations that eliminate the need for the most constraining assumptions. For example, in the hedonic model, we might look for a more generalized form of the supply function that would still allow us to identify a demand curve for "beach cleanliness." We might also want to consider disequilibrium situations, where excess demand or excess supply exists in the market. In the latter case we must develop some data bases that will allow better estimates of the key parameters of both the ecological and economic models. In this study we are trying to determine a set of characteristics which describe recreational beaches, and to measure these characteristics. In general, however, information on the attributes of recreational or aesthetic environments that are important to consumers, and on which of these attributes might be affected, in what way, and for how long by an environmental perturbation such as an oil spill, is inadequate. There are numerous other questions which need to be answered as well. Fish population models, for example, seldom include environmental variables, in part

because of a paucity of data on such variables. It is doubtful that the point of diminishing returns to investments in improved information is close at hand. The problem is more that efforts have been somewhat ad hoc rather than directed toward identifying the crucial gaps information and designing research projects to fill them. Improved estimates of benefits and costs can in themselves increase the net benefits from our use of these resources.

Footnotes

[1]The research discussed in this paper is supported under contract number MO-A01-78-00-4086 from the Office of Ocean Management, National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The findings expressed are those of the author, and not those of the U.S. Department of Commerce.

[2]While the Supreme Court affirmed the district court ruling that the State of Washington's Tanker Law is unconstitutional because of being preempted by the federal Ports and Waterways Safety Act, the Coast Guard has, in response to this decision, established an interim navigation rule prohibiting the entry into Puget Sound of oil tankers in excess of 125,000 dead weight tons (Coast Guard 1978).

[3]The Supreme Court recently declined to review the case of County of Suffolk v. Department of Interior, thus allowing to stand the lower court decision which reversed the nullification of the leases. The Massachusetts v. Andrus challenge on the other hand was based on the inappropriateness of the Secretary's decision to make the sale before passage of the Outer Continental Shelf Lands Act Amendments. A preliminary injunction has been granted; however, disposition on the merits is yet to come. However, should the amendments become law before this time the preliminary injunction will have been successful. (Federal Court Caps OCS Oil and Gas Lease Sales 1978).

[4]The California Plan has since been approved. However, its enforceability awaits consideration of the case on its merits (American Petroleum Institute v. Knecht 1977).

[5]The Massachusetts Plan has since been fully approved. It is likely to come to trial on its merits sometime this summer.

[6]S. 9 and H.R. 1614 are companion bills. S. 9 has passed both the Senate and the House and is, as of this writing, in conference.

[7]Two key concepts in the measurement of economic value are consumers' surplus and producers' surplus (or rent). The former represents the amount consumers would be willing to pay for a good or service, over and above its cost to them. The latter represents the amount producers receive for supplying a good or service, over and above the cost to them.

[8]Having information on income levels of consumers of different types of accommodations in different areas will also enable us to say something about how the costs implied by the losses in economic value of beach services are distributed, an important consideration from the point of view of economic welfare.

[9] A related question is that of the appropriate degree of expenditure on clean up. The problem has both economic efficiency considerations, in that once a spill has occurred we want to choose a clean up cost-damage cost combination that minimizes overall costs, and distributional considerations in that we may only want the cost minimizing solution if the distribution of the costs is deemed acceptable.

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THE IMPACT OF THE ARGO MERCHANT SPILL (12/15/76)

Chairman: JAMES MATTSON
National Advisory Committee on Oceans and Atmosphere

EVIDENCE OF ARGO MERCHANT CARGO OIL IN MARINE BIOTA BY GLASS CAPILLARY GC ANALYSIS

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ABSTRACT

Thirty-seven samples of marine biota collected in response to the *Argo Merchant* oil spill were analyzed for hydrocarbons by glass capillary gas chromatography (GC). Rapid, temperature programmed analysis of hydrocarbons from n-$C_{10}H_{22}$ to n-$C_{34}H_{70}$ was demonstrated on a 2-m glass capillary. Analysis time was 7 minutes *vs.* 40 minutes or more on a 2-m packed column of comparable resolution. Finely detailed high resolution gas chromatograms were obtained on 20-m glass capillaries. The GC patterns of the saturated hydrocarbons extracted from marine biota were visually compared with the corresponding GC pattern from the *Argo Merchant* cargo. The stomach contents from two cod samples and one windowpane flounder sample afforded finely detailed gas chromatograms of saturated hydrocarbons that compared well with the cargo chromatogram. Analogous comparisons of the aromatic hydrocarbons confirmed the correlation for only one of the samples from cod.

INTRODUCTION

After the tanker *Argo Merchant* broke up on the Nantucket Shoals off Massachusetts in December 1976, its 7.7 million gallon cargo of No. 6 fuel oil drifted across important marine fishing areas. In response to this threat to marine resources, the National Marine Fisheries Service (NMFS) sampled marine biota in the vicinity of the oil slick (Fig. 1) for the analyses discussed here (Grose and Mattson 1977). Thirty-seven samples from ten species were analyzed for hydrocarbons by high resolution gas chromatography to elicit evidence of contamination by the spilled *Argo Merchant* cargo.

It is well known that petroleum and its fuel oil products are subject to a number of physical, chemical, and biological processes upon release into the marine environment (Clark and MacLeod 1977). Depending on many factors, these "weathering" processes can alter the original hydrocarbon composition of a spilled oil, eventually beyond recognition. Many of these processes, especially hydrocarbon sorption and partitioning and transformations by tissue, detritus, and sediment need to be understood much better before the fate of spilled oils in environmental samples can be entirely rationalized (Farrington and Medeiros 1975, Roubal *et al.* 1978). Despite such problems, hydrocarbons found in environmental samples may be linked to a suspected source of oil, if detailed and discriminating physicochemical data from the sample and suspected source of hydrocarbons closely agree.

High resolution gas chromatography (GC) is an example of a technique which can provide highly detailed physicochemical data when it is applied to compositional analysis of extremely complex mixtures of hydrocarbons, such as make up petroleum. Several years ago Adlard et al. (1972) demonstrated that high resolution GC with metal capillary columns could extensively separate (resolve) individual compounds from such mixtures. The detailed patterns of these hydrocarbon distributions were used to differentiate stranded oils. Recent glass capillary GC columns permit greater resolution and provide finely detailed gas chromatograms to characterize hydrocarbon distribution patterns from marine sediments, biota, and fuel oils (MacLeod et al. 1977ab & 1978ab, Ramos et al. 1978, Brown et al. 1978).

As environmental processes continue to alter the distribution patterns of hydrocarbons, establishment of a relationship between hydrocarbon patterns from an environmental sample and a suspected oil source becomes increasingly difficult. The use of pattern matching or data ranking procedures for these detailed hydrocarbon distributions may contribute to an understanding of the fate of these hydrocarbons in the marine environment. A recent review on the utilization of analytical instrumentation to fingerprint or match oil samples (Bentz 1976) showed little use being made of the fine detail from high resolution GC. Hence, it is timely that the wealth of definitive information obtainable by glass capillary GC analysis be considered in oil identification strategies for environmental samples.

In this study, finely detailed gas chromatograms of both saturated and aromatic hydrocarbons from samples of marine biota collected in relation to the Argo Merchant spill were compared with the analogous chromatograms from the cargo oil. If sample and reference GC patterns corresponded closely upon visual inspection, a probable match with the cargo oil was indicated.

METHODS AND MATERIALS

Samples of marine biota were collected during two cruises of the R/V Delaware II (Fig. 1) using standard NMFS groundfish survey procedures (Grose and Mattson 1977). All samples were frozen until analyzed, generally as composites from three or more individuals of a species. The composite samples were then homogenized, digested with alkali, solvent extracted, chromatographed on silica gel, analyzed by glass capillary GC and mass spectrometry (MS), according to published procedures (MacLeod et al. 1977ab). In most instances these procedures incur hydrocarbon losses of 10-15% during sample workup; relative standard deviations are ≤20% for most hydrocarbon quantitations. The GC internal standard was hexamethylbenzene. High resolution gas chromatograms of the saturated and aromatic hydrocarbons from the samples were compared, peak for peak, with the corresponding reference chromatogram from the Argo Merchant cargo.

RESULTS AND DISCUSSION

Glass Capillary Gas Chromatography

Figure 2 shows a low resolution gas chromatogram of the saturated hydrocarbons from the Argo Merchant cargo. It is comparable to other published chromatograms of Argo Merchant oil (Grose and Mattson 1977, Hoffman and Quinn 1978), but with an important difference: it was obtained in 7 minutes with a 2-m glass capillary column. Since a standard GC analysis of petroleum hydrocarbons (e.g., n-C_{10}-C_{34}) on 2-m packed columns requires 40 minutes or more, considerable time can be saved by using a short glass capillary. This is particularly useful for screening large numbers of samples.

Perhaps the most significant feature of glass capillary GC is the ability of longer columns (e.g., 20-30 m) to separate individual compounds in complex hydrocarbon mixtures more completely than any other technique. The ultimate achievement of this performance capability has been implicit in research with metal GC capillaries over the past decade (Modzeleski et al. 1968, MacLeod 1968, Adlard et al. 1972, Zafiriou 1973). Nevertheless, standard GC procedures for analysis of petroleum have favored the use of low resolution packed GC columns over metal capillaries. Reasons for this include the greater cost and expertise associated with capillary GC, plus the very long analysis times required for extensive resolution of the more complex petroleum mixtures by the best metal capillaries. However, now that higher resolution glass capillary GC columns are generally available, the great complexity of petroleum fractions can be extensively resolved in analyses so routine that they may be automated (MacLeod et al. 1977ab & 1978ab, Ramos et al. 1978, Brown et al. 1978).

The wealth of detailed information on the composition of complex hydrocarbon mixtures obtainable with glass capillary GC (or GC/MS) is an important factor that should not escape the attention of those involved with fingerprinting oil or tracing its fate in the aquatic environment. More definitive information can be obtained by glass capillary GC or GC/MS than by any other method. Examples of this detail are shown in Figures 3 and 4. Note that in the high resolution gas chromatogram of the Argo Merchant saturated hydrocarbons (Fig. 3) there is almost as much information detailed in the intervals between adjacent n-alkanes (e.g., peaks 10-11, 11-12, etc.) as in an entire packed column chromatogram (similar to Fig. 2). Horizontal scale expansion of Figure 3 revealed 15-40 discrete hydrocarbon components in each of these intervals. These routine, automated glass capillary gas chromatograms clearly demonstrate that standard packed column GC procedures that partially resolve only 20-30 prominent hydrocarbons (e.g., the n-alkanes) are not the best available technology for routine oil analysis.

High Resolution GC Pattern Comparisons

The most direct evidence of contamination by the Argo Merchant cargo was found in the GC patterns of the hydrocarbons from a few samples of fish stomach contents. Hydrocarbons extracted from the

stomach contents of the cod collected on cruise DE 77-01, station 29 correlated best with the cargo hydrocarbons. Upon visual inspection, the high resolution gas chromatogram of the saturated hydrocarbons (Fig. 5) corresponded well with the reference pattern (Fig. 3). A similar close correspondence was found between the aromatic hydrocarbons of this sample (Fig. 6) and the reference (Fig. 4). Both finely detailed sample GC patterns show such complete qualitative agreement with their counterparts from the Argo Merchant cargo that it would be difficult to deny that the stomach contents of this cod had been contaminated with Argo Merchant oil.

The saturated hydrocarbons from the stomach contents of windowpane flounder collected on cruise DE 76-13, station 4 also gave a GC pattern (Fig. 7) which compared well with Figure 3. However, the level of individual major alkanes (10-100 ppb) was much lower than that of the cod stomach (10-30 ppm) above, and few arenes could be measured with certainty. Thus, while spilled Argo Merchant cargo may have been ingested by the windowpane flounder, the evidence is not as strong as with the cod.

Another sample of cod stomach contents (cruise DE 77-01, station 38) showed low levels of major saturated hydrocarbons whose GC pattern (Fig. 8) was similar to the reference pattern (Fig. 3) in some details, but differed conspicuously in others. The aromatic hydrocarbon abundances were too low for reliable comparison. None of the remaining 33 samples of biota gave high resolution gas chromatograms of saturated or aromatic hydrocarbons which could be matched with Figures 3 and 4 by inspection.

SUMMARY

Glass capillary GC proved extremely useful in the analysis of samples collected after the Argo Merchant oil spill. The use of short glass capillaries (2 m) substantially reduced GC analysis times compared to packed columns of comparable resolution (7 min vs. 40+ min). GC analyses on longer columns (20 m) provided extensive detail on hydrocarbon distribution patterns from samples of marine biota and the Argo Merchant cargo. Almost as much information on hydrocarbon distribution was available between adjacent n-alkanes of the high resolution glass capillary gas chromatogram of Argo Merchant oil as in an entire packed column chromatogram. Since these high resolution GC analyses were achieved routinely with automatic sample injection and data processing, it is clear that glass capillary GC columns deserve more general application to routine oil spill analyses.

The best evidence of contamination by Argo Merchant oil was found in the hydrocarbons of the stomach contents of a cod. The high resolution gas chromatograms of both the saturated hydrocarbons and the aromatic hydrocarbons appeared extremely similar to their counterparts from the Argo Merchant cargo oil. A sample of stomach contents from windowpane flounder compared almost as well in the saturated hydrocarbons, but the amounts of aromatics were too low for comparison. Another sampling of cod stomach contents displayed only partial similarity to the cargo saturated hydrocarbons, while the aromatics were

not measurable. The remaining 33 samples of marine biota showed no definitive evidence of contamination by spilled Argo Merchant cargo.

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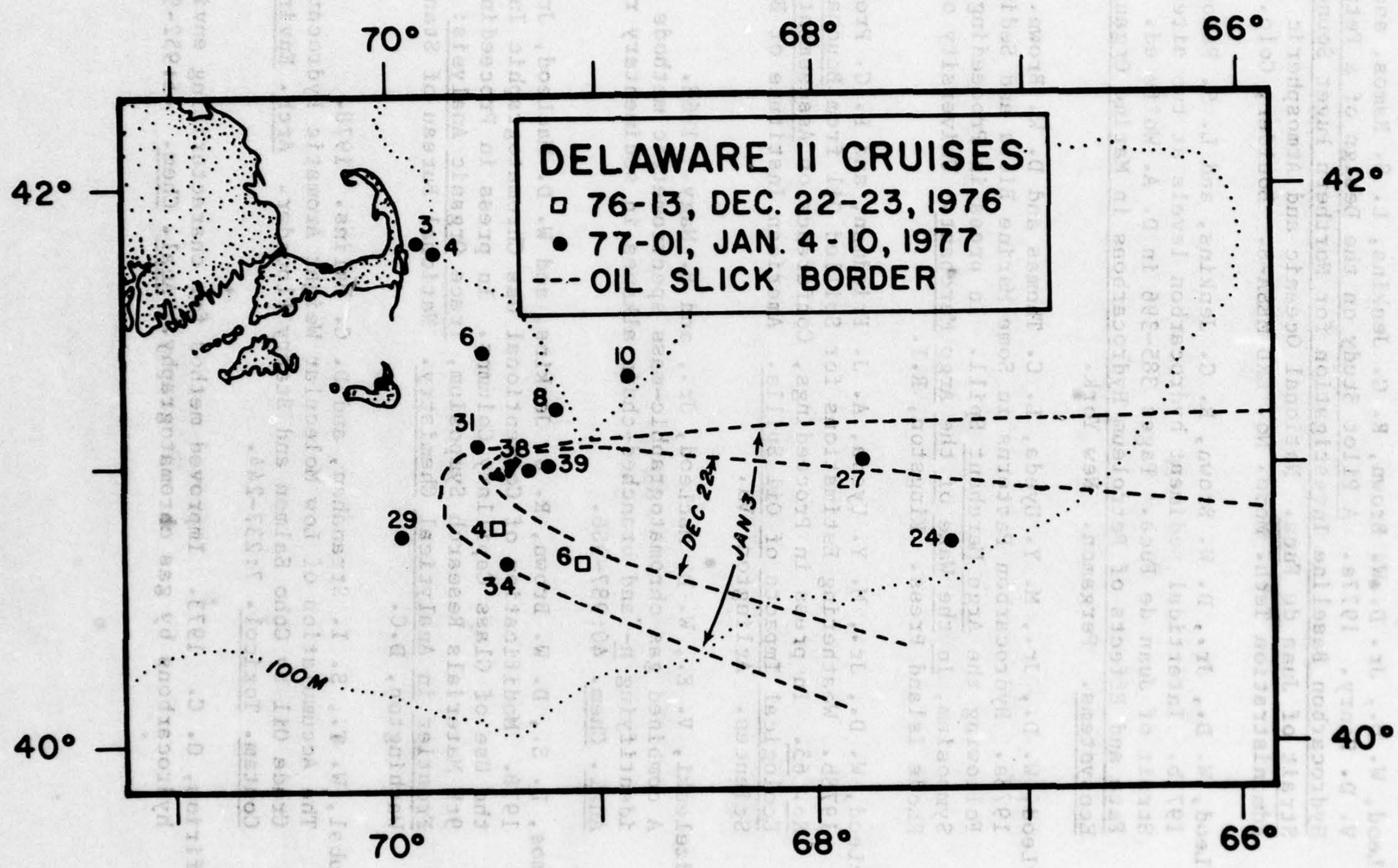

Figure 1. Collection locations for samples of marine biota taken during cruises of the R/V Delaware II (MacLeod et al. 1978a).

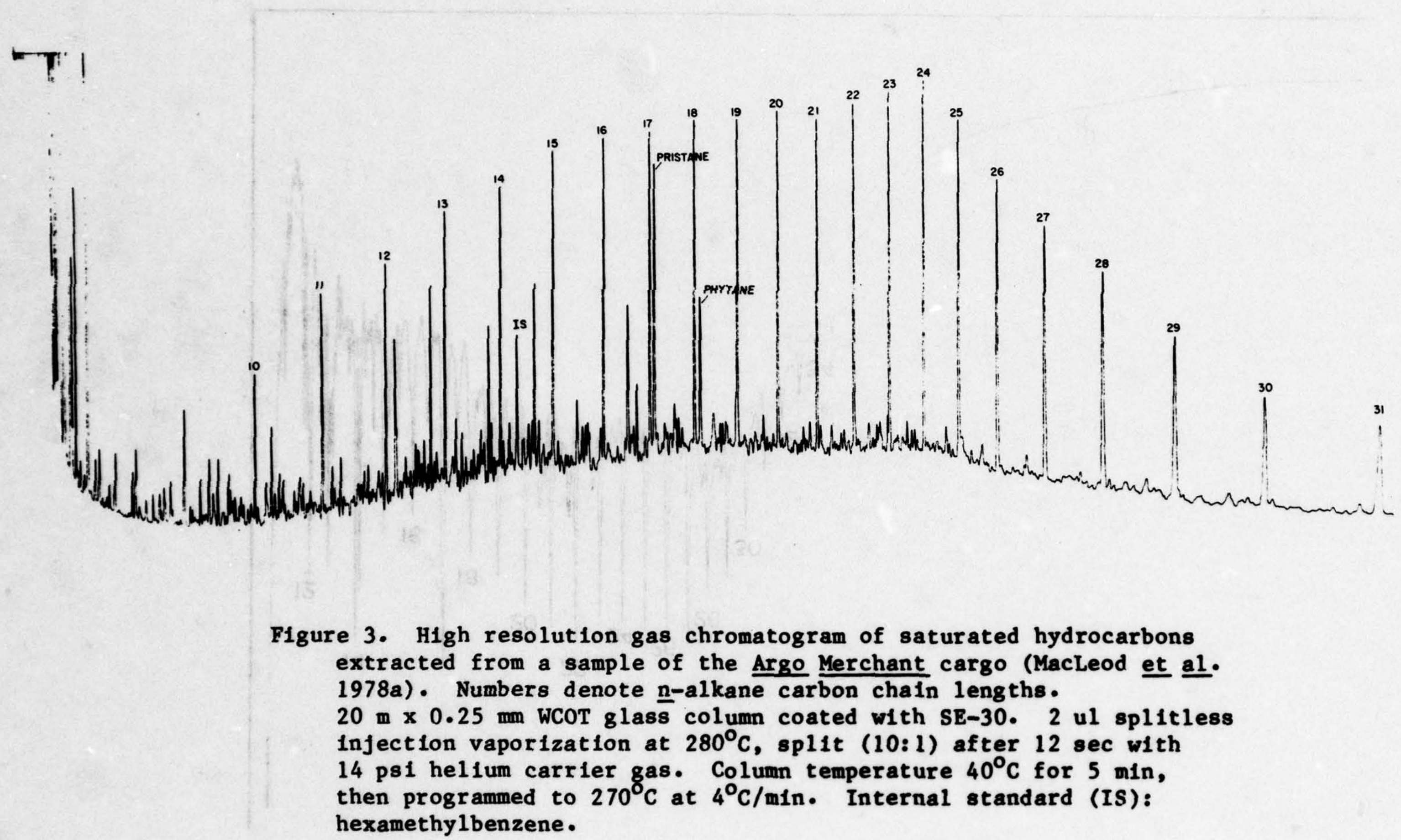

Figure 3. High resolution gas chromatogram of saturated hydrocarbons extracted from a sample of the Argo Merchant cargo (MacLeod et al. 1978a). Numbers denote n-alkane carbon chain lengths. 20 m x 0.25 mm WCOT glass column coated with SE-30. 2 ul splitless injection vaporization at 280°C, split (10:1) after 12 sec with 14 psi helium carrier gas. Column temperature 40°C for 5 min, then programmed to 270°C at 4°C/min. Internal standard (IS): hexamethylbenzene.

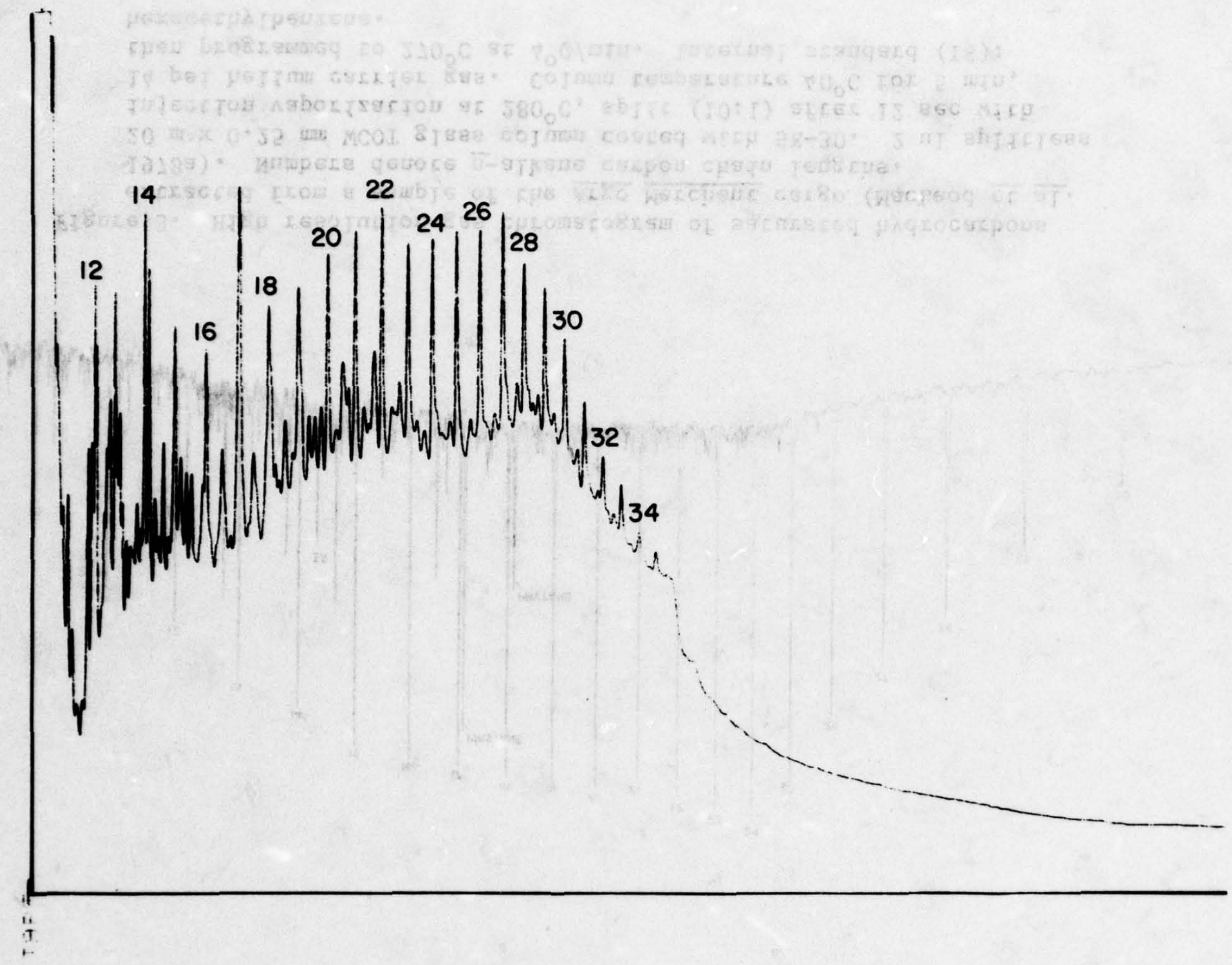

Figure 2. Gas chromatogram of Argo Merchant cargo oil. Numbers denote n-alkane carbon chain lengths. 2 m x 0.25 mm WCOT glass column coated with SE-54. 10 ug of oil in 2 ul of pentane solution injected, vaporized at 280°C, and split 10:1. Carrier gas pressure 14 psi helium. Column temperature 75°C for 36 sec, then programmed to 280°C at 30°C/min.

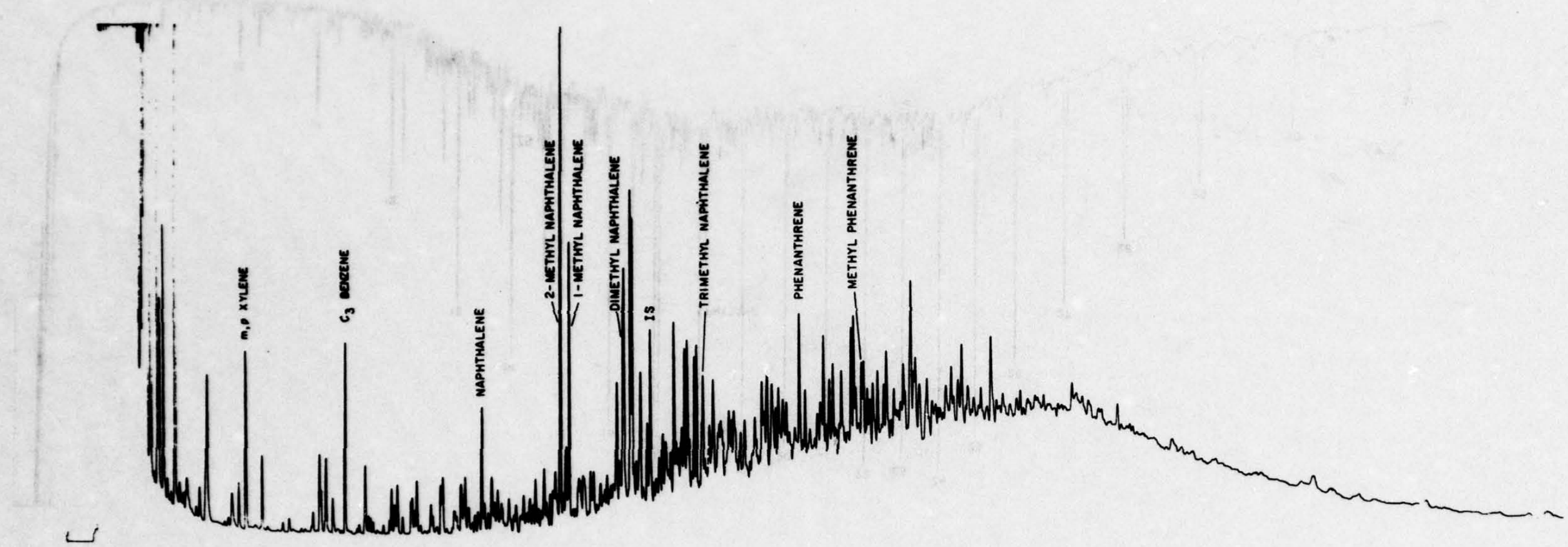

Figure 4. High resolution gas chromatogram of saturated hydrocarbons extracted from the stomach contents of cod collected on cruise DE 77-01, station 29 (MacLeod *et al*. 1978a). Numbers denote *n*-alkane carbon chain lengths. Conditions same as for Figure 3.

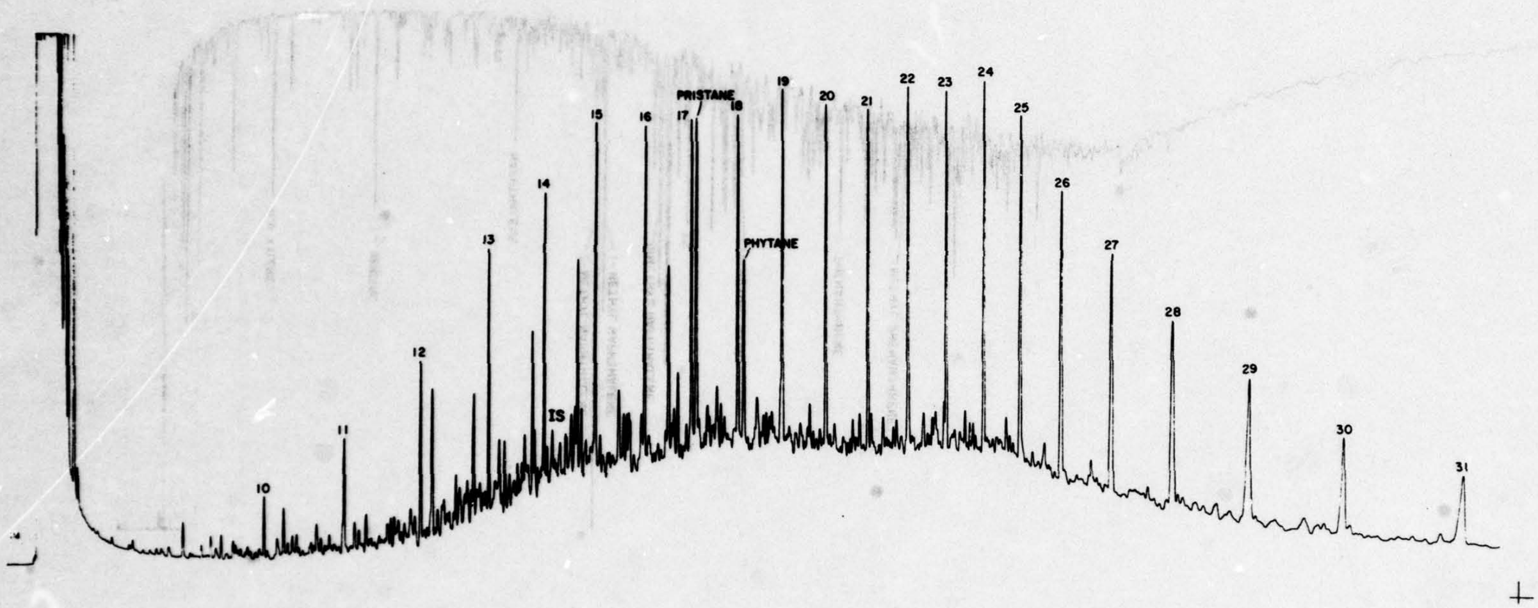

Figure 5. High resolution gas chromatogram of aromatic hydrocarbons extracted from a sample of the __Argo Merchant__ cargo (MacLeod __et al.__ 1978a). Conditions same as for Figure 3. Identified compounds confirmed by mass spectrometry.

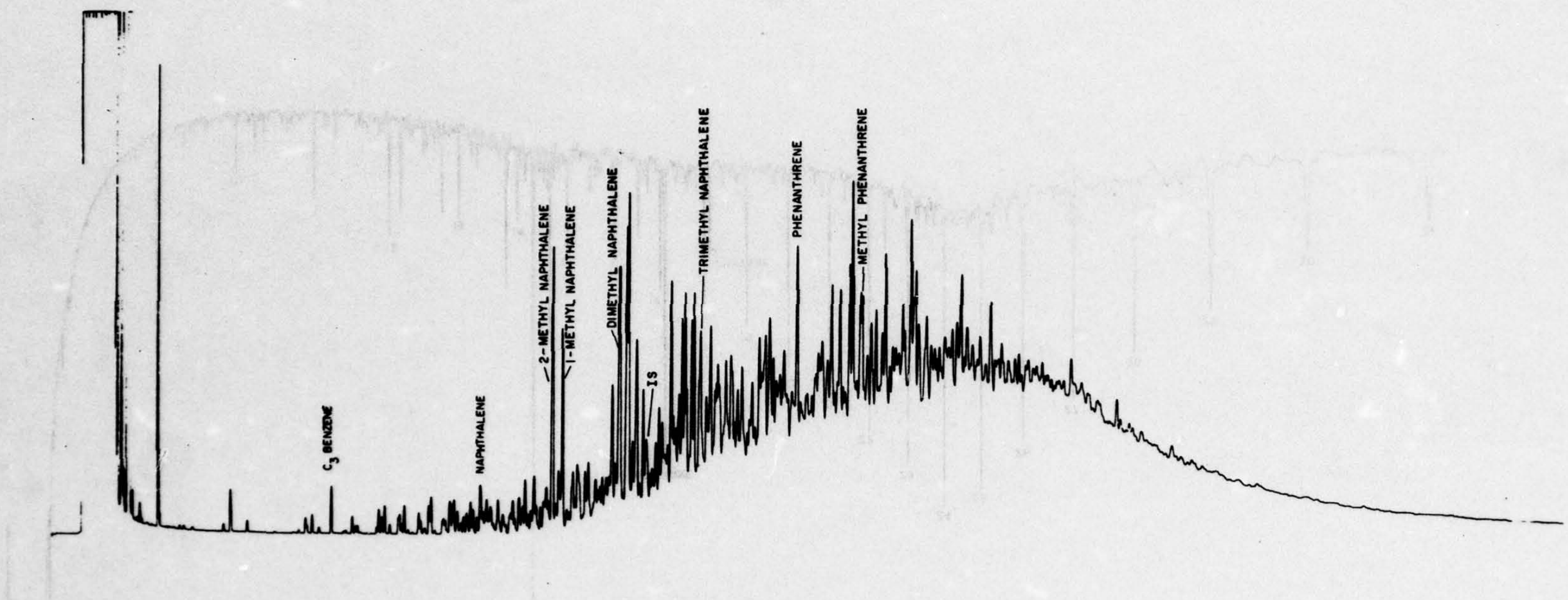

Figure 6. High resolution gas chromatogram of aromatic hydrocarbons extracted from the stomach contents of cod collected on cruise DE 77-01, station 29 (MacLeod <u>et al</u>. 1978a). Conditions same as for Figure 3. Identified compounds confirmed by mass spectrometry.

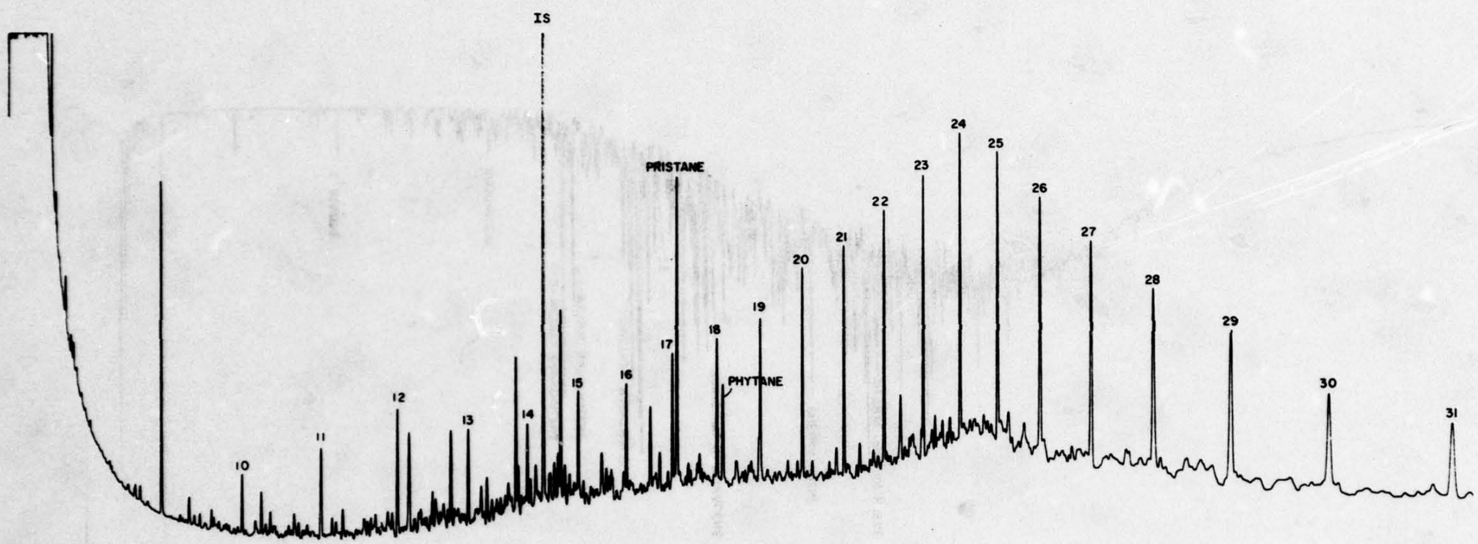

Figure 7. High resolution gas chromatogram of saturated hydrocarbons extracted from the stomach contents of windowpane flounder collected on cruise DE 76-13, station 4 (MacLeod et al. 1978a). Conditions same as for Figure 3. Numbers denote n-alkane carbon chain lengths.

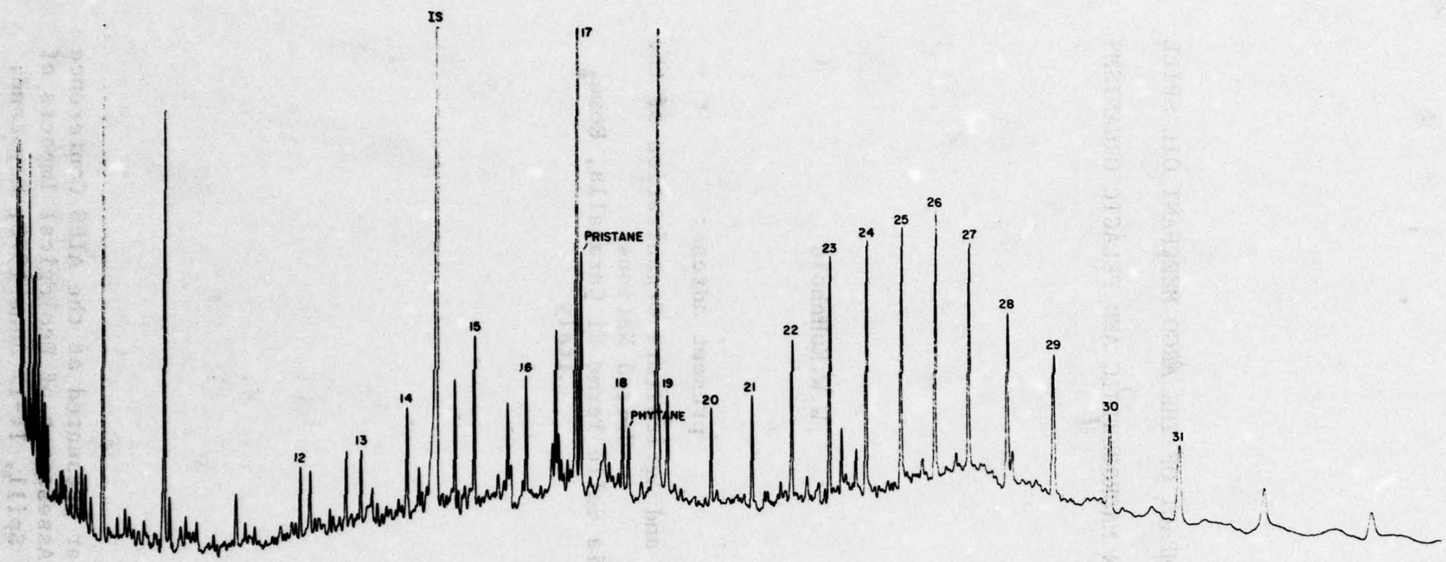

Figure 8. High resolution gas chromatogram of saturated hydrocarbons extracted from the stomach contents of cod collected on cruise DE 77-01, station 38 (MacLeod et al. 1978a). Conditions same as for Figure 3. Numbers denote n-alkane carbon chain lengths.

IMPACT OF THE ARGO MERCHANT OIL SPILL ON MACROBENTHIC AND PELAGIC ORGANISMS

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(Paper presented at the AIBS Conference on Assessment of Ecological Impacts of Oil Spill, 14-17 June 1978, Keystone, Colorado, U.S.A.)

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ABSTRACT

Abundance studies in benthic and pelagic communities including commercial fish species were done but did not suggest a major adverse impact. Zooplankton was, at some stations, fouled with oil. At some stations within the slick area and close to the margin lower densities of ichthyoplankton were found; pelagic fish eggs of the only two species present were contaminated and found moribund to a high degree. Laboratory experiments with cod eggs and young larvae were conducted with a no.6 fuel oil to determine toxic levels of dissolved hydrocarbon concentrations. Very few of the fish examined, showed traces of ARGO MERCHANT oil in stomach contents or muscle tissue. Prey-predator relationship seemed to have remained normal. Shortcomings in sampling methodology and evaluations are discussed.

INTRODUCTION

"The oil tanker ARGO MERCHANT ran aground on Fishing Rip, 29 nautical miles southeast of Nantucket Island, Massachusetts, on December 15, 1976. At the time she was carrying 7,700,000 gal of No. 6 fuel oil, most of which was released into the environment on December 21 when the ship broke in half. This resulted in one of the largest and most extensively studied oil spills in U.S. history (Grose and Mattson, 1977).

Following the ARGO MERCHANT shipwreck a number of biological studies were initiated to assess the impact of the oil on the ecosystem. Although winds and currents carried the oil offshore, thus eliminating the direct threat of oil on the New England coast, there was concern about the effect of oil on the fish stocks. Contamination of the fish, or fish eggs, and their invertebrate prey could have a long-term effect on the Georges Bank fishery" (Bowmann and Langton, 1978).

The purpose of this paper is not to compile the detailed results of all biological investigations carried out during the various cruises following the ARGO MERCHANT-tanker accident, but to attempt a critical evaluation of the findings reported by the researchers of different biological disciplines. Comprehensive compilations of the cruise reports, methods and findings are given in the Preliminary Report on the Spill (Grose and Mattson, 1977) and in the Proceedings of the ARGO MERCHANT symposium (

However, a short summary of the studies will be given here and some of the results will need a review in more depth for a better understanding of the biological situation and characteristics. Most studies were based on - sometimes repeated - sampling carried out within 12 months following the spill. It is the unanimous opinion of all researchers - as expressed during the final panel discussion of the ARGO MERCHANT symposium - that more and better immediate studies could have been done under a better developed response plan. This means that adequate scientific response to an acute oil spill would have required better scientific tactics, an "emergency-plan", quick availability of specialized ship board equipment for biological assays, and methods applicable for spill-field-tests. Moreover a better coordination of all actions undertaken by the different scientific disciplines,mainly hydrochemicals,is needed in order to ensure better interpretation of the biological data.

Notwithstanding these limitations, the effort to measure the impact of the ARGO MERCHANT oil spill on the biota of the Nantucket shoals was quite remarkable.

The evaluation in this paper of the results obtained shall be done from several points of view:

1) What degree of contamination of the studied biota was observed ?

2) Did the investigations indicate any detrimental impact on a) individuals b) populations ?

3) Do the obtained data permit a realistic assessment of the impact on the populations ?

4) Which kind of data were missing for a comprehensive assessment ?

The answer to these questions may also facilitate the answer of the final programmatic question to be discussed at the end of this symposium:

What did we learn from comparing the oil spill studies,
What should have been studied, and
What should we study in a future spill case ?

SUMMARY OF ACTIVITIES AND ANALYSES ON BENTHIC AND PELAGIC COMMUNITIES (Table 1)

Benthic organisms

Repeated Smith-McIntyre grab samples and scallop dredge samples were made 2, 6, 6 to 8, 9 to 10 weeks and 7 months after the tanker accident and preserved in formalin. Samples from the immediate vicinity were compared with those taken 30 and more miles away. All samples were analysed for abundance of macrobenthic and meiobenthic organisms, for impact of oil on the organisms as well as for accumulation of hydrocarbons in the sediment (Pratt, 1978; Hoffman and Quinn, 1978). Due to the type of preservation, only hard bodied meiofauna could be identified later on. Individuals of many groups -- fish, molluscs, crustaceans, sea urchins and starfish -- collected at stations in the immediate vicinity of the ship wreck, although visibly uncontaminated by particulate oil, were examined for histological lesions in various tissues. Only one individual of the larger species, a *Cancer* crab, was found heavily impacted with oil (Sawyer, 1978; Brown and Cooper, 1978).

Fishery

Besides examination of individual specimens fishery surveys were made within close range of the tanker wreck as well as in the larger area of Georges

Table 1: Summary of research activities and analyses of benthic and pelagic communities after the ARGO MERCHANT spill in December 1976, as reported during the symposium "In the wake of the ARGO MERCHANT", January 1978.

Preliminary results but also more detailed data on most of the section were also given in the Preliminary Scientific Report: The ARGO MERCHANT Oil Spill (Grose and Mattson, 1977)

Activity	Analysis	Institutions involved in research	Publishing author(s)
Macrobenthos	Abundance	Univers. RI,	Pratt
	Histopathology	Univers. RI, NMFS, Oxford,	Brown and Cooper Sawyer
	Biochemistry	NMFS, Milford	Thurberg et al.
	HC-Chemistry	NMFS, NAF, Seattle, Wash., Univers. RI,	MacLeod et al. Hoffmann and Quinn
Zooplankton, gen.	Abundance	NMFS, Narrag.,	Sherman and Busch
	HC-Chemistry Histology	McGill Univers., Montréal,	Polak et al.
Ichthyoplankton	Abundance	NMFS, Narrag.,	Sherman and Busch
	Genetics	NMFS, Milford	Longwell
	Laboratory exp.	IfM, Kiel	Kuhnhold
Fish Fishery	Abundance pelagic demersal	NMFS, Narrag., Woods Hole,	Sherman and Busch
	Prey-Predation	NMFS, Woods Hole	Bowmann and Langton
	Biochemistry	NMFS, Milford,	Thurberg et al.
	HC-Chemistry	NMFS, Seattle	MacLeod et al.

Bank. Monthly catch data from commercial landings were compiled for the area in the vicinity of the wreck for 1975, 1976, and 1977. To allow for changes in the distribution of the stocks, catches from a wider area encompassing both Nantucket Shoals and Georges Bank were analyzed. Independant information on fish abundance was obtained from the results of the spring and autumn bottom trawl surveys conducted as part of the Marine Resources Monitoring Assessment and Prediction Program (MARMAP) of the National Marine Fisheries Service. The surveys have been made continuously off the northeast coast for the past 15 years by the Northeast Fisheries Center (Grosslein, 1976).

The Northeast Fisheries Center examined in specific the catches for two years (1975, 1976) prior to the spill to identify the most abundant species in the spill area. The three most frequently caught species were: cod, sea scallops and winter flounder, the first being pelagic, the latter two benthic species. A consortium of 5 non-profit fisheries organizations initiated and carried out a program aimed at determining the impact of the oil on the fish of the Nantucket area in a draft report (Development Sciences, 1977). Their results indicated that the only oil damage was limited to the observation of oil in the stomach of two codfish shortly after the spill.

The stomach contents of 21 species of fish and squid were analyzed to determine the potential impact of the ARGO MERCHANT-oil on the fish stocks on Georges Bank (Bowmann and Langton, 1978). The purpose of this investigation was also to verify the known food habits of marine fish and squid in the spill area, and to demonstrate the potential pathways for the transfer of oil residues through the food web. Besides the two most abundant demersal species, selected individuals of 3 more demersal species and 3 pelagic fish species have been analyzed for oil contamination, specifically for comparison with the original cargo of the ARGO MERCHANT (MacLeod et al., 1978). Physiological and biochemical assays were undertaken in teleosts and some molluscs. Ocean scallops (*Placopecteus magellanicus*) and horsemussels (*Modiolus modiolus*), collected at 3 and 9 weeks after the spill, were tested for oxygen consumption, and various metabolic reactions as malic dehydrogenase activity, lactate oxidation and pyruvate reduction. Blood samples were taken from 3 pelagic fish species, a serum parameter and ion composition were compared to fish from unimpacted areas (Thurberg et al., 1978).

Plankton

During most of the cruises zooplankton and ichthyoplankton samples were collected with paired 60 cm bongo nets towed obliquely through the water column from just off bottom to the surface at 1.5 Knts. Also, surface plankton was collected with 0.5 m x 1.0 m neuston net towed at the surface at 1.5 Knts. The first collection was made one week after the spill began, the last, so far listed in publication, in October 1977. Samples were analysed for species abundance, primarly petroleum hydrocarbon analyses were made of zooplankton samples from three different cruises until March 1977 (dates and stations listed in Sherman and Busch, 1978). In some samples, showing a rather high percentage of visible oil-contaminated zooplankters, selected individuals were microscopically inspected and histological preparation were made (Polak et al., 1978; Kuhnhold, 1978b). As in many samples, fish eggs also showed visible oil contamination on the chorion. The methodology for studying cell damage in fish eggs on the chromosome level was applied to these samples (Longwell, 1978). Moreover, laboratory tests with developing cod eggs and larvae were run to provide an idea of the toxic level of dissolved hydrocarbons present from heavy fuel oil (no. 6) (Kuhnhold, 1978a).

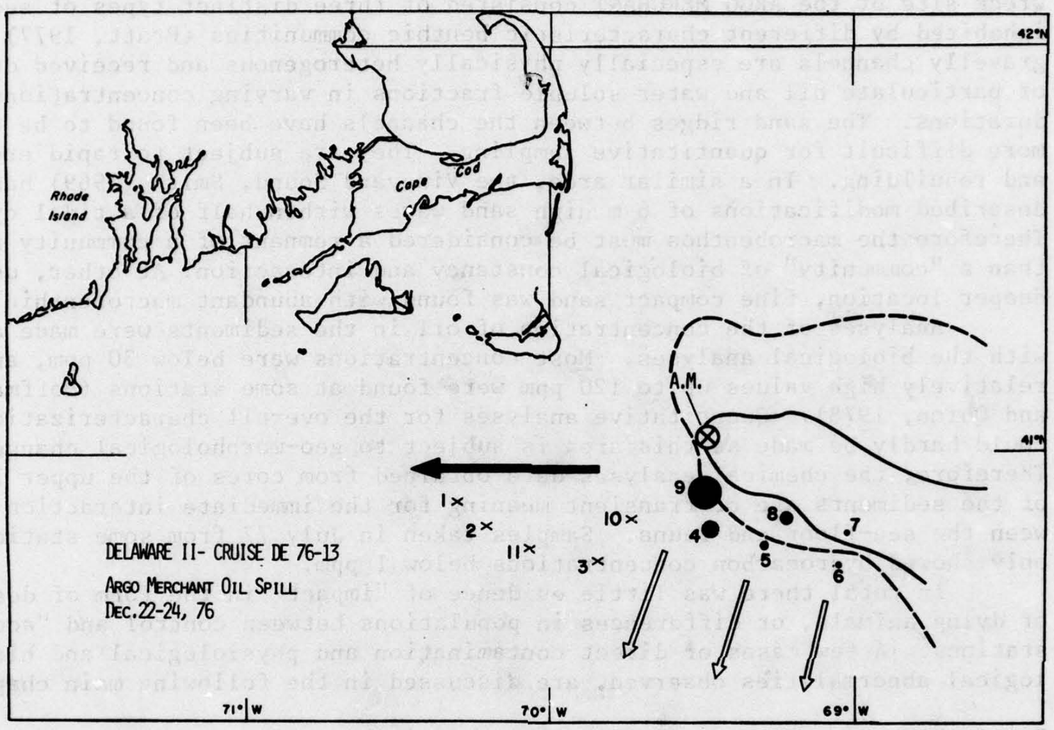


Fig. 1. Location of ARGO MERCHANT grounding, showing borders of observed oil slick as of 22 Dec. (solid line) and 23 Dec. (broken line). Numbers indicate stations of sampling (St. 1, 22 Dec. to St. 11, 23 Dec.). Solid circle are relative measures for number of zooplankters per 100 m^3. Open arrows indicate movement of southern margin of oil slick. Solid arrow indicates mean direction of sea current (from Grose and Mattson, 1977).

ABUNDANCE OF FAUNA

Benthos

The number of samples obtained from the cruises did not allow a very comprehensive synopsis of the bottom fauna. Moreover other difficulties of physical nature made the analyses more complex. The sea floor around the wreck site of the ARGO MERCHANT consisted of three distinct types of sediment, inhabited by different characteristic benthic communities (Pratt, 1977). The gravelly channels are especially physically heterogenous and received doses of particulate oil and water soluble fractions in varying concentrations and durations. The sand ridges between the channels have been found to be even more difficult for quantitative sampling. They are subject to rapid erosion and rebuilding. In a similar area, the Vineyard Sound, Smith (1969) has described modifications of 6 m high sand waves within half of a tidal cycle. Therefore the macrobenthos must be considered a remnant of a community rather than a "community" of biological constancy and interaction. At other, usually deeper location, fine compact sand was found with abundant macrobenthic species.

Analyses of the concentration of oil in the sediments were made along with the biological analyses. Most concentrations were below 30 ppm, and relatively high values up to 120 ppm were found at some stations (Hoffmann and Quinn, 1978). Quantitative analyses for the overall characterizations could hardly be made as this area is subject to geo-morphological changes. Therefore, the chemical analyses data obtained from cores of the upper layer of the sediments are of transient meaning for the immediate interaction between the sea-floor and fauna. Samples taken in July 77 from some stations only showed hydrocarbon concentrations below 1 ppm.

In total there was little evidence of "impact" in the form of dead or dying animals, or differences in populations between control and "accident" stations. A few cases of direct contamination and physiological and histological abnormalities observed, are discussed in the following main chapter.

Zooplankton

The communities of zooplankton in the vicinity of the spill were described in the NOAA-report (Grose and Mattson, 1977). Biomass determination were made with samples taken on a cruise one week after the spill, and these ranged from 2.0 to 16.4 ml/100 m^3. The lowest biomass was measured at stations within the observed boundaries of the oil slick. Similar low values were also found next to this station within and also outside the slick area. The highest values were obtained at 2 stations (4 and 9) at the west end of the visibly contaminated area, one being on the boundary of the slick, and one clearly outside, but not too far away from the oil slick. Zooplankton numbers also followed trends in biomass (Fig. 1).

Ichthyoplankton studies showed: larvae of six species were present but only the sand launce (*Ammodytes americanus*) was very abundant. At 3 sampling stations (6, 7 and 8 (Fig. 1)), the abundance of the sand launce larvae decreased sharply (Fig. 2). At the station further west, outside the slick area, the number of larvae increased again, however, the depressed abundance at station 6 was also west of the periphery of the visible slick. There is no direct indication whether this is associated with the negative effects on the viability of larvae or whether it reflects the "patchiness" of larvae distribution. Although not important for commercial fisheries, sand launce is

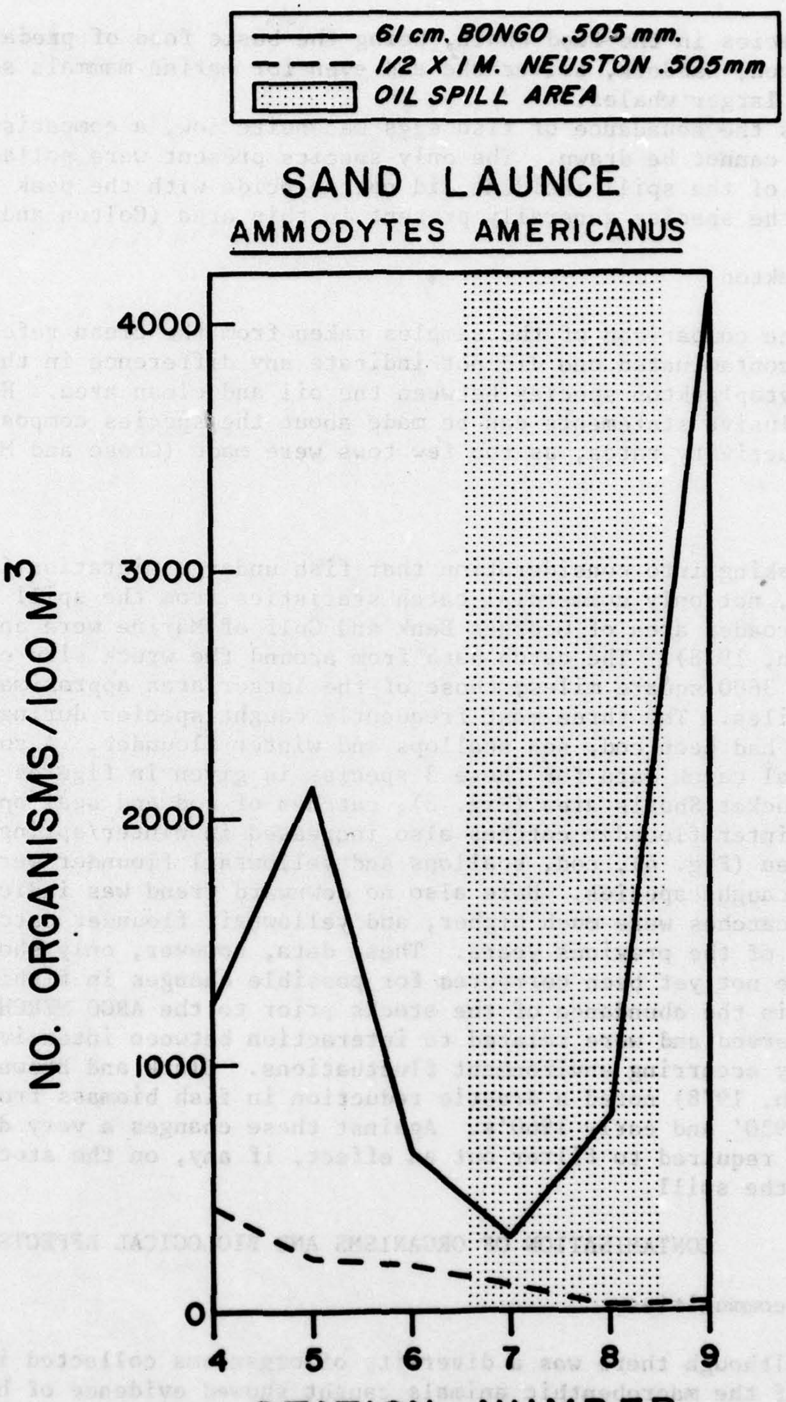


Fig. 2. Abundance of sand launce larvae at stations outside and within the borders of the visible oil slick (see fig. 1) (from Sherman and Busch, 1978).

a key species in the food chain, being the basic food of predatory fish as e.g. cod, haddock, silverhake and even for marine mammals such as porpoises and also larger whales.

As the abundance of fish eggs was quite low, a comparison between stations cannot be drawn. The only species present were pollack and cod. The time of the spill incident did not coincide with the peak of spawning of most the species generally present in this area (Colton and Onge, 1974).

Phytoplankton

The comparison of the samples taken from the clean reference station and the contaminated one did not indicate any difference in the abundance of major phytoplankton species between the oil and clean area. However, hardly any conclusive statements can be made about the species composition, abundance, and productivity rates, as too few tows were made (Grose and Mattson, 1977).

Fish

Taking into consideration that fish undergo migration for feeding and spawning, not only commercial catch statistics from the spill zone but also from a broader area of Georges Bank and Gulf of Marine were analysed (Sherman and Busch, 1978). The catch data from around the wreck site comprised approximately 3600 square miles, those of the larger area approximately 54,000 square miles. The three most frequently caught species during the years 1975 and 1976 had been cod, sea scallops and winter flounder. A summary of monthly commercial catch data for these 3 species is given in figures 3 and 4. In the Nantucket Shoals area (Fig. 3), catches of cod and scallops increased in 1977. Winter flounder catches also increased in winter/spring 1977. For the total area (Fig. 4), cod, scallops and yellowtail flounder were the most frequently caught species. Here also no downward trend was indicated. Cod and scallop catches were much higher, and yellowtail flounder catches were similar to those of the previous years. These data, however, only show trends, as they have not yet been corrected for possible changes in fishing effort. Changes in the abundance of the stocks prior to the ARGO MERCHANT spill have been observed and were related to interaction between intensive fishing and naturally occurring environment fluctuations. Clark and Brown (1977 in Sherman and Busch, 1978) noted a drastic reduction in fish biomass from former levels in the 1950' and early 1960's. Against these changes a very detailed analysis would be required to filter out an effect, if any, on the stocks in the vicinity of the spill.

CONTAMINATION OF ORGANISMS AND BIOLOGICAL EFFECTS

Benthic communities

Although there was a diversity of organisms collected in the dredges only 3 of the macrobenthic animals caught showed evidence of heavy oil contamination. It appeared in a starfish in the form of several tarry lumps in the buccal cavity. A rock crab (*Cancer borealis*) was found dead, after it had obviously fed on ARGO MERCHANT oil which filled the entire stomach. One moribund hermit crab (*Pagurus longicarpus*) also contained a brown oily substance in the digestive tract. All other animals collected were alive and showed no visible oil contamination nor abnormal behavior.

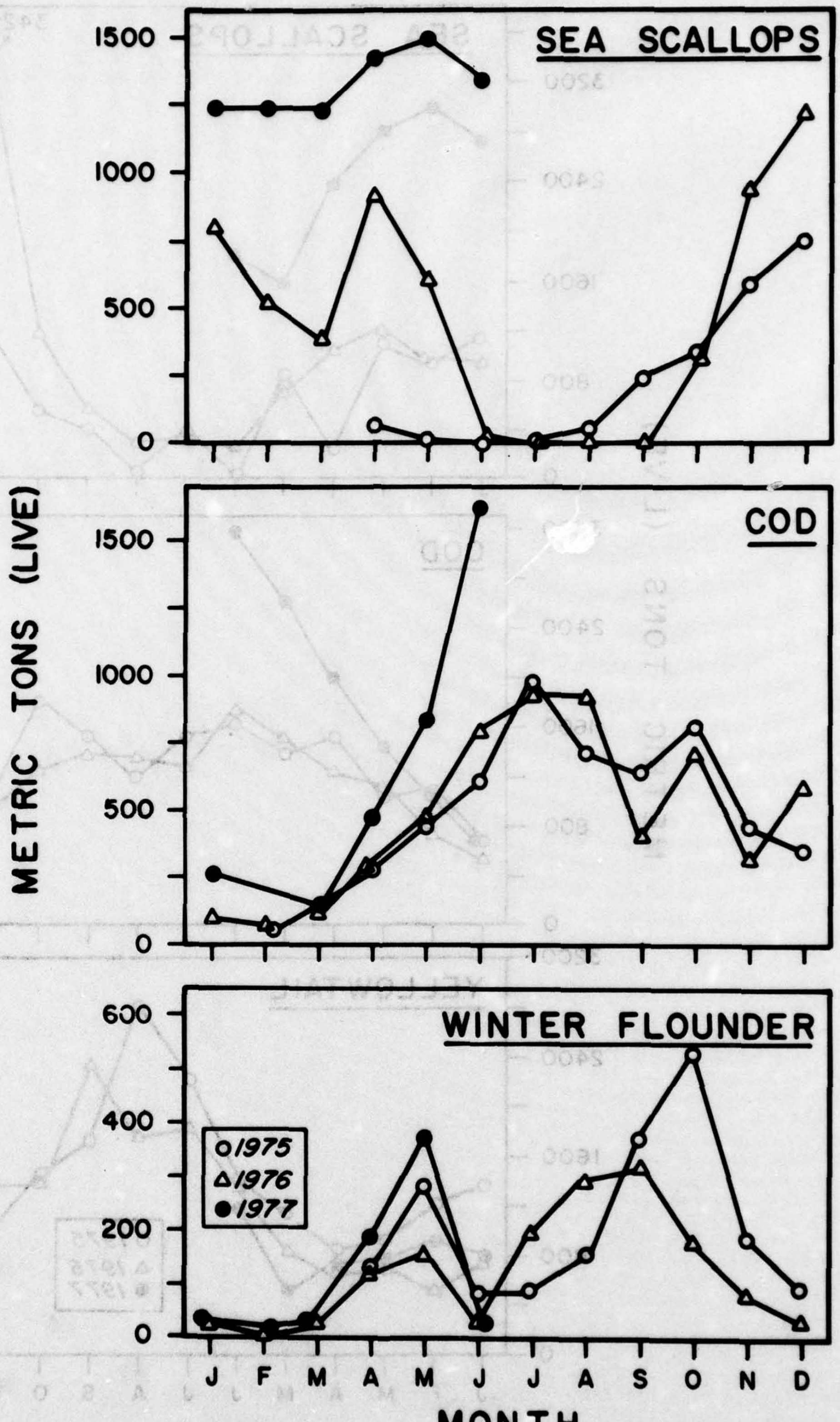


Fig. 3. Total monthly catches of sea scallops, cod, and winterflounder, the three most abundant species, in Nantucket Shoals area, for 1975 to 1977. Data are not corrected for differences in catch effort (from Sherman and Busch, 1978).

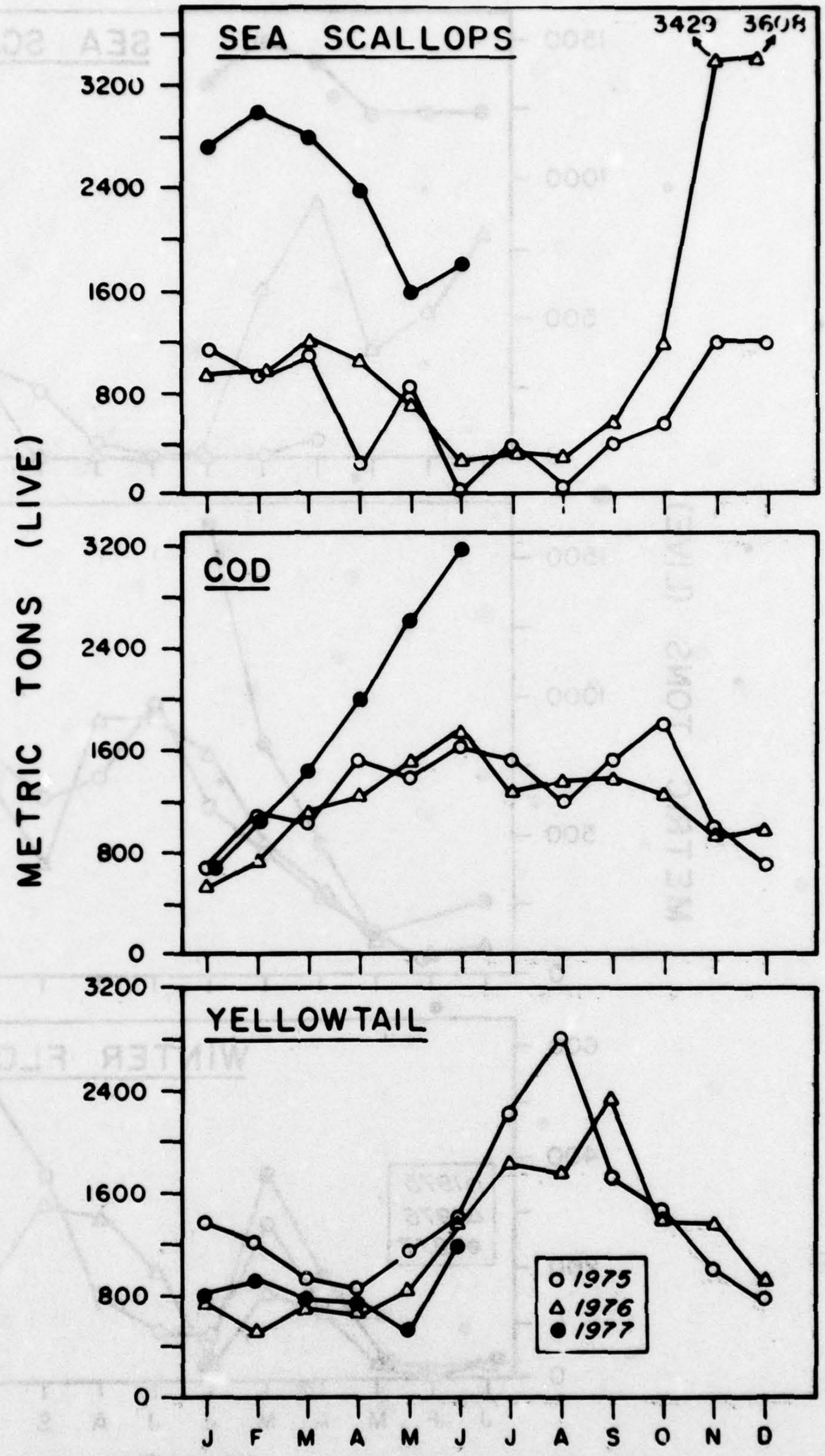


Fig. 4. Total monthly catches of sea scallops, cod, and yellowtail flounder, the three most abundant species in Georges Bank/Gulf of Maine area, for 1975 to 1977. Data are not corrected for differences in catch effort (from Sherman and Busch, 1978).

Histological inspections of animals of many families showed various abnormalities in some specimens: edematous gills were found in alewives and winter flounder, hyperplastic olphactory epithelium in yellowtail flounder, ocular lesions in larvae of the sand launce (*Ammodytes americanus*), lack of pigmentation of the eye, and many other abnormalities. None of the conditions observed, however, could be attributed directly to the effects of spilled oil. Astonishingly,molluscs, sea urchins, and starfish were free of pathological appearances.

The physiological and biochemical studies in those ocean scallops and horsemussel collected shortly after the spill gave lower than normal values for oxygen consumption of the gill tissue, but did not show any sign of stress in specimens collected six weeks later (Fig. 5). The decrease in enzyme activities and in metabolic measurements in muscle tissue that are typically found in anoxic glycolysis suggests a possible weakening in the ability to shift to anaerobiosis, a characteristic feature in bivalves (Thurberg et al., 1978). However, the authors themselves indicate that a difference in the treatment of the animals, deep freezing in the first case and holding alive until disection in the second case, may cause analytical differences. It would be unsound to draw general conclusions from the few data obtained, but the authors also state that it would be unwise to ignore indications of stress revealed in the data.

Zooplankton

A significant contamination was found in pelagic crustaceans. The dominant species in the area of investigation was the copepod *Centropages typicus*, a food species of both larval and adult fish. Many crustaceans were contaminated externally with oil particles coating feeding appendages, carapace, and extremities. Large numbers of *Centropages* (Fig. 6), *Parathemisto*, and *Gammarus* had also clearly ingested oil particles. Microscopical inspection, disection, and histological preparation show the particularized oil adhering to the stomach and gut walls (Fig. 7 and 8). Although there is close contact with the digestive epithelium, there is no evidence whether the "digestion of oil" had any detrimental effect on these animals. Fig. 9 also shows that the oil, once ingested, passes the alimentary tract, is encapsuled in the normal fecal pellet, and is "discharged" from the animal.

It seemed very obvious that the organisms could have been fouled in the nets which would collect oil particles from the water column filtered. Polak et al. (1978) made an attempt to correlate net and plankton fouling. Figures 10a and 10b show the results of extracts from 1 ml of zooplankton and a swatch of net gauze. The size of the washed net gauze was a few cm^2, and the resulting values (ppm) shown are the concentrations of oil in the obtained extracts, compared with standards of ARGO MERCHANT-oil solutions.

The data show that in cases of high contamination with oil of the plankton (up to 50 ppm, w/v) the contamination of the net is 8-100 fold less. This correlation, however, contains several shortcomings: the size of the washed net material is arbitrary and not comparable to the volume of plankton extracted. Moreover, there is no indication, and this was the question to solve, how much of the oil particles collected adhere to the net, how much is collected in the bucket and what portion is finally adhering to the plankton surface. The oil may not even have been adsorbed on the gauze, but only collected in the bucket. The authors did not separate plankton organisms that only showed clear evidence of previously ingested oil. A distinction between fouling inside the net and definite oil-contamination prior to net contact of the plankton is still not safely possible.

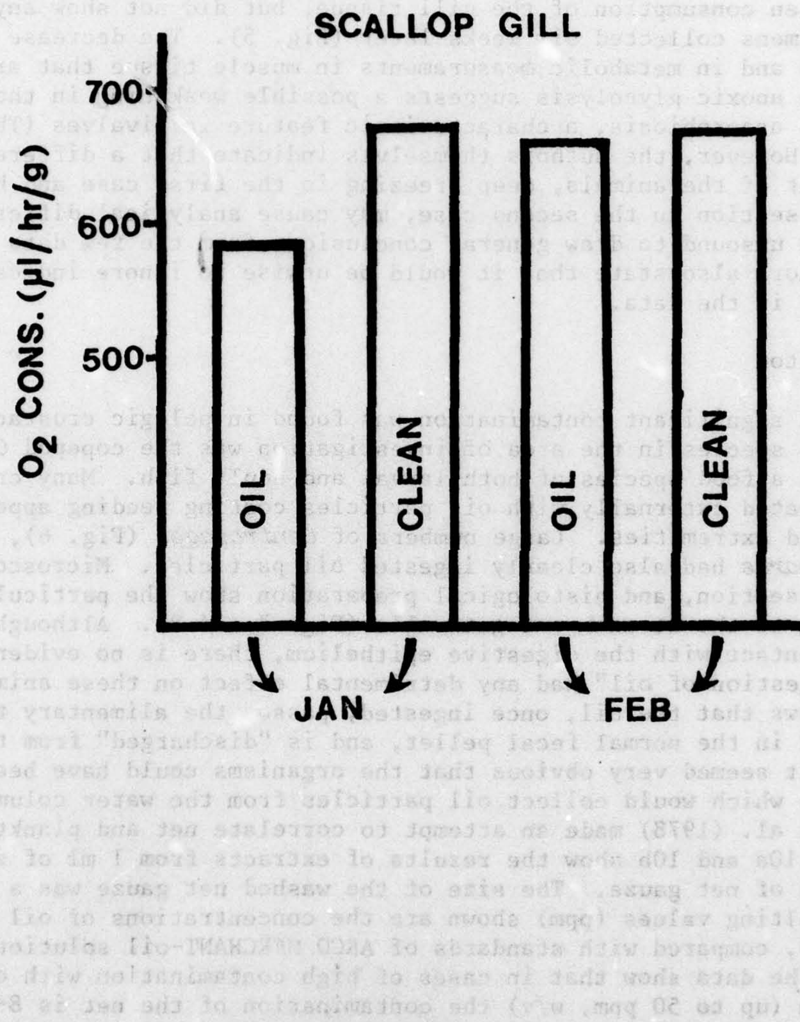


Fig. 5. Gill-tissue oxygen consumption values of sea scallops, *Placopecten magellanicus*, taken from oil-impacted areas (n :7 and 9) and adjacent clean areas (n :5 and 9) in January and February 1977 (from Thurberg et al., 1978).

Fig. 6. Copepod, *Centropages typicus*, having ingested oil particles, gathered in the stomach (dark spot in center) (Photograph: R. Cohen, NMFS, NEFC, Woods Hole).

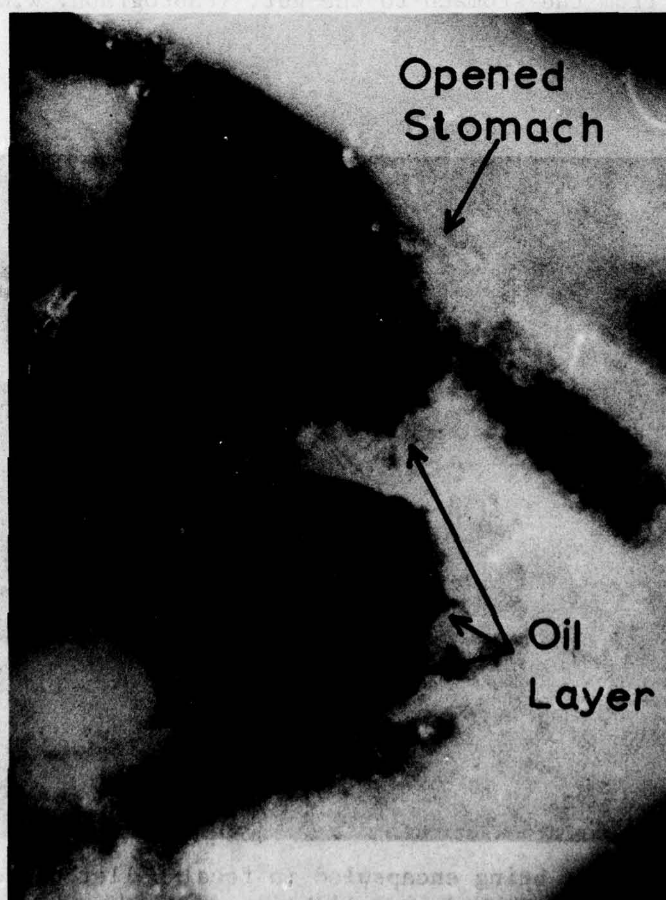
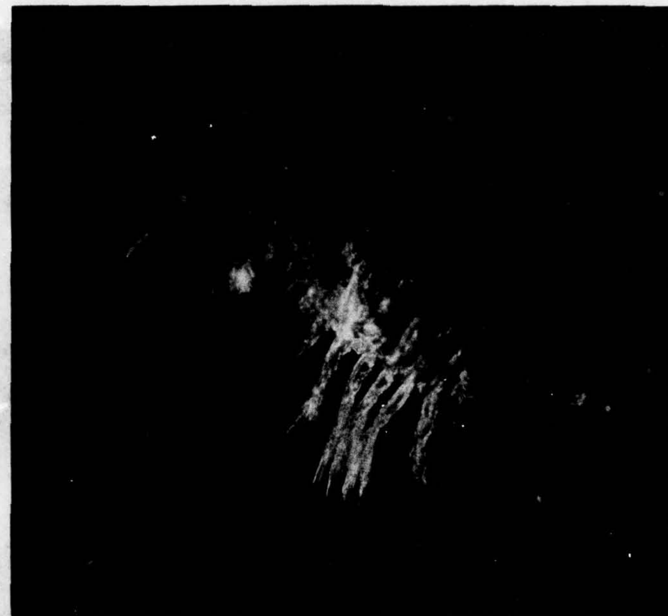


Fig. 7. Disected stomach of an amphipod *Parathemisto* sp., showing ingested oil adhering to stomach wall. (Photograph: W.W. Kuhnhold).



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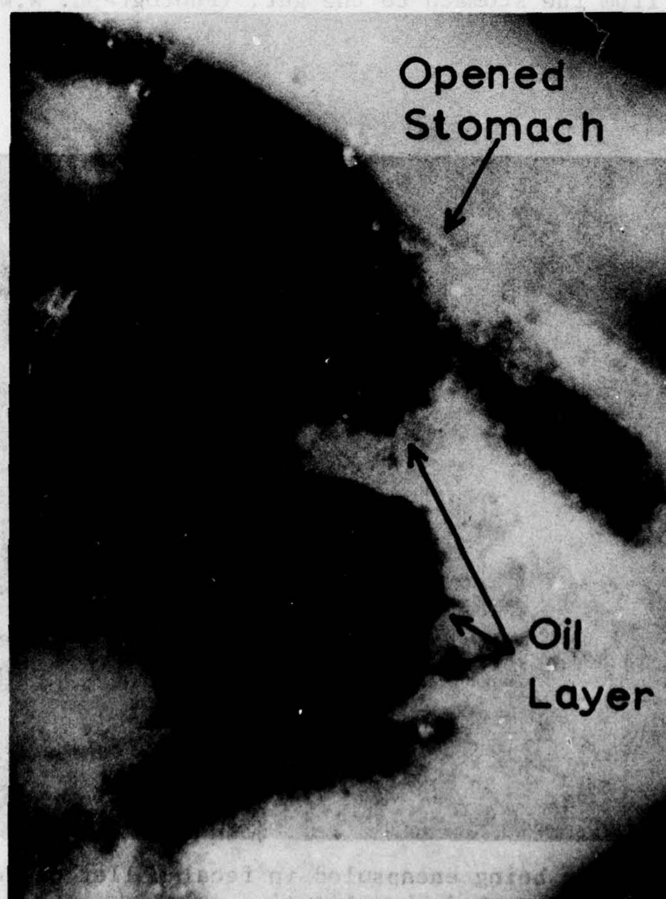

Fig. 7. Disected stomach of an amphipod *Parathemisto* sp., showing ingested oil adhering to stomach wall. (Photograph: W.W. Kuhnhold).

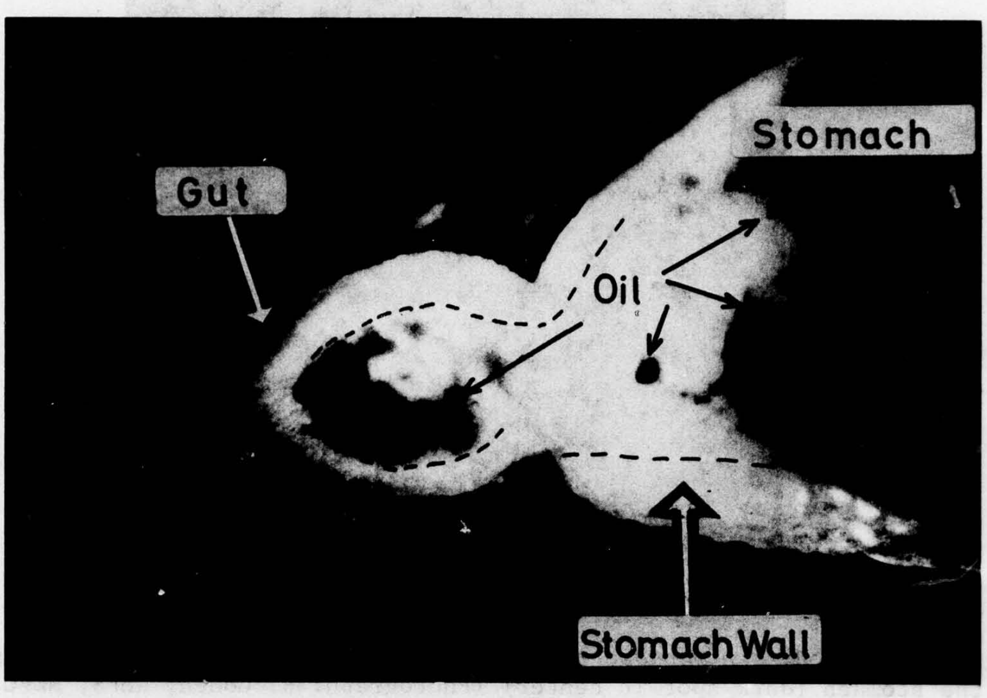

Fig. 8. Stomach and part of gut of a copepod, *Centropages typicus*, showing oil being passed from the stomach to the gut. (Photograph: W.W. Kuhnhold).

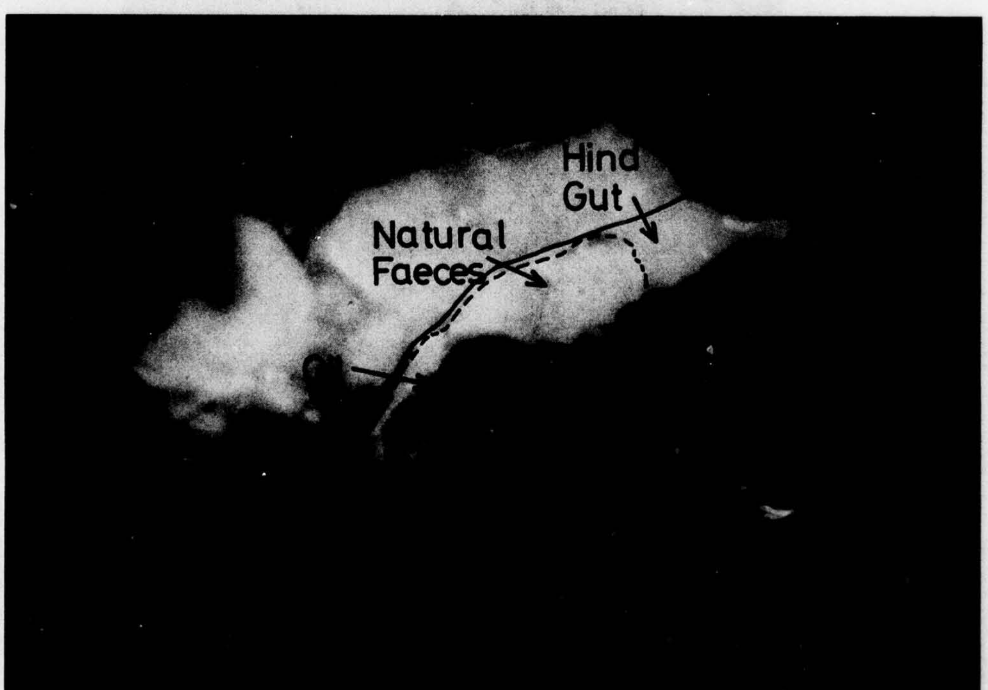

Fig. 9. Oil particles being encapsuled in fecal pellet of copepod, *Centropages typicus*. Gut wall marked by solid line, pellet membrane emphasised by dashed line.(Photograph: W.W.Kuhnhold)(Original photos in colours,except fig.6)

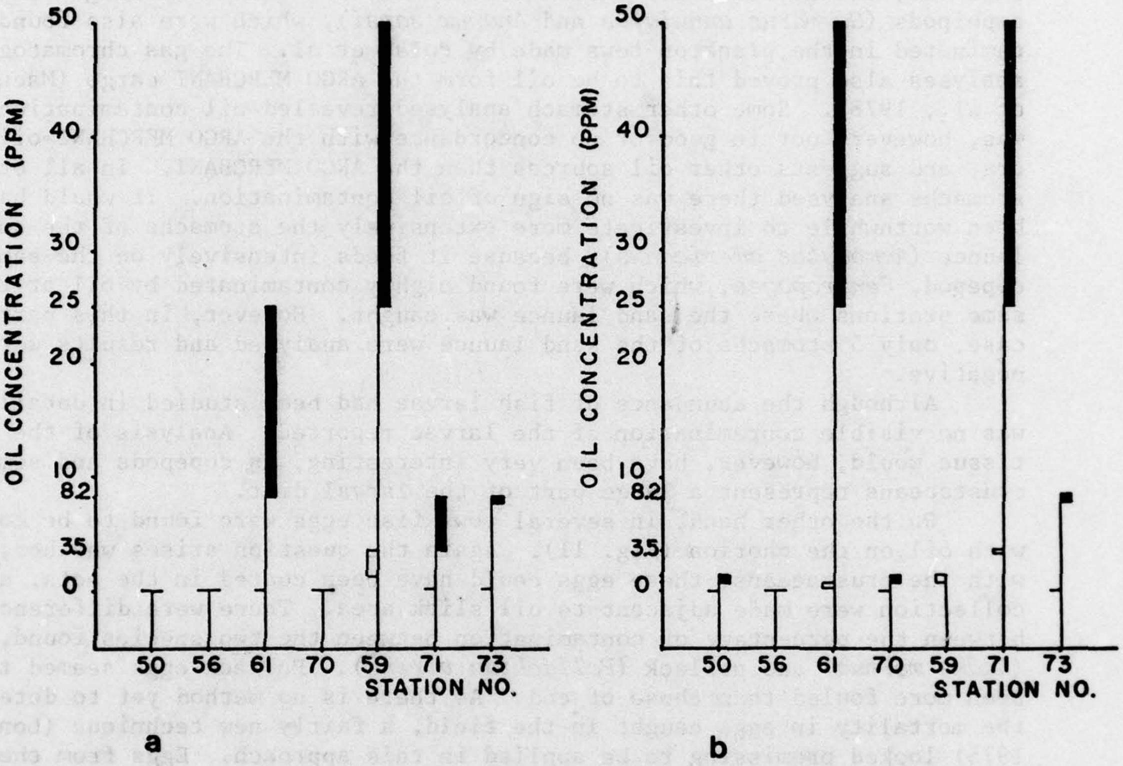

Fig. 10a, b. Comparison of oil contamination in plankton vs net a) 333 u mesh size b) 505 mesh size. Open barrs = net, solid barrs = plankton. Station numbers refer to station of ENDEAVOR 005 cruise, Feb. 1977 (from Polak et al., 1978).

The investigation, however, shows that there are generally no contaminated nets when the plankton has remained clean. Still, there is evidence of true contamination as mentionned in the following paragraph.

Fish

When studying the prey-predation relationship in the ARGO MERCHANT spill region, few stomachs contents of fish contained food organisms fouled with oil; two Atlantic cod stomachs contained oil-contaminated gammeridean amphipods (*Gammarus annulatus* and *Anonyx sarsi*), which were also found contaminated in the plankton tows made by Polak et al. The gas chromatographic analyses also proved this to be oil form the ARGO MERCHANT cargo (MacLeod et al., 1978). Some other stomach analysed revealed oil contamination which was, however, not in good or no concordance with the ARGO MERCHANT oil spectra, and suggests other oil sources than the ARGO MERCHANT. In all other stomachs analysed there was no sign of oil contamination. It would have been worthwhile to investigate more extensively the stomachs of the sand launce (*Ammodytes americanus*), because it feeds intensively on the same copepod, *Centropages*, which were found highly contaminated by oil at the same stations where the sand launce was caught. However, in this particular case, only 5 stomachs of the sand launce were analysed and results were negative.

Although the abundance of fish larvae had been studied in detail, there was no visible contamination of the larvae reported. Analysis of the larvae tissue would, however, have been very interesting, as copepods and some other crustaceans represent a large part of the larval diet.

On the other hand, in several tows fish eggs were found to be coated with oil on the chorion (Fig. 11). Again the question arises whether, as with the crustaceans, these eggs could have been coated in the nets, as collection were made adjacent to oil slick area. There were differences between the percentage of contamination between the two species found, cod (*Gadus morhua*) and pollack (*Pollachius virens*). Pollack eggs seemed to have been more fouled than those of cod. As there is no method yet to determine the mortality in eggs caught in the field, a fairly new technique (Longwell, 1975) looked promissing to be applied in this approach. Eggs from the contaminated samples as well as from clean reference station were investigated for cytogenetic abnormalities. The mitotic index, indicating the progression cell division was taken as criterion for moribundity. Totalled over all stations, more pollack eggs were moribund or dead (46%) than cod eggs (20%). Control eggs from laboratory-spawned cod showed only 4% of mortality at the same stage. For laboratory experiments this value may be representative, and if it is also valid for the field, then cod showed a higher than normal mortality, but still less than pollack. At station 8 within the more heavily oiled area pollack embryos were malformed in 18% of the eggs collected (Fig. 12). At the periphery of the polluted area (station 9, Fig. 1) only 9% were found malformed. None of the cod eggs showed similar features nor did any of the pollack eggs at more distant reference stations. Oil has never been observed adhering to the many planktonic fish eggs studied at the Milford Lab (Longwell, 1978), with only one exception of mackerel eggs from New York Bight. This direct contact of oil with eggs, the external fouling on the eggs membrane *if not* proved an artifact of sampling, is very important, as it indicates that many more eggs will be exposed to the dissolved hydrocarbons than those showing this evidence of oil exposure. The sensivity of eggs and larvae to dissolved hydrocarbons in the water column will be discussed in a later chapter.

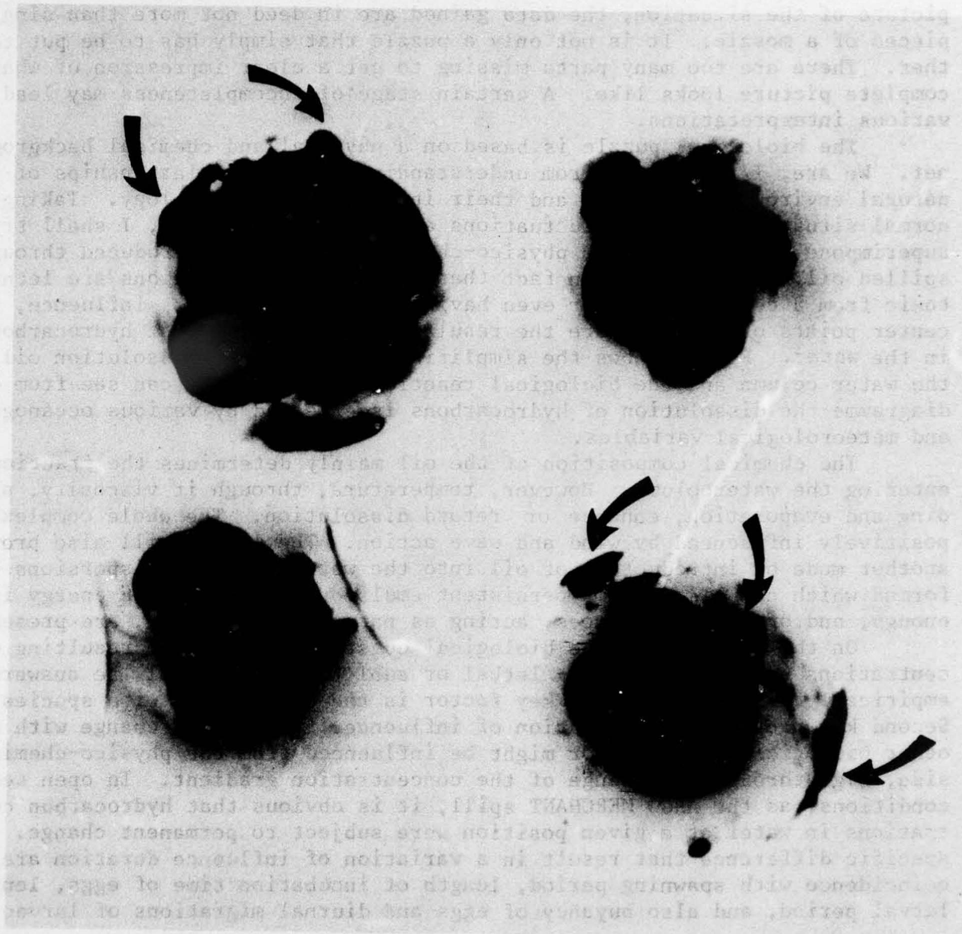

Fig. 11. *Pollock eggs sampled at edge of the ARGO MERCHANT oil slick. Tail-bud and tail-free embryo stages. Egg at upper left and egg at lower right with outer membrane contaminated with a tar-like (Arrows). The uncontaminated egg at upper right has a malformed embryo. The uncontaminated egg at lower left is collapsed and also has an abnormal embryo (collapse of membrane certainly due to mechanical stress and preservation). Actual size of pollack eggs around 1 mm (from Longwell, 1978).*

ASSESSMENT OF DAMAGE TO THE FAUNAL COMMUNITIES

General situation in an oil spill

So far we have been observing a diverse spectrum of effects on the fauna. Inspite of the effort and intention to get an as complete as possible picture of the situation, the data gained are in deed not more than single pieces of a mosaic. It is not only a puzzle that simply has to be put together. There are too many parts missing to get a clear impression of what the complete picture looks like. A certain stage of incompleteness may lead to various interpretations.

The biological puzzle is based on a physical and chemical background net. We are, I think, far from understanding all interrelationships of the natural environmental factor and their influence on the ecology. Taking the normal situation with its fluctuations as a given basic grid, I shall try to superimpose this grid by the physico-chemical situation introduced through spilled oil. Taken the known fact that dissolved oil fractions are lethally toxic from a certain level or even having a sublethal stress influence, the center points of interest are the resulting concentrations of hydrocarbons in the water. Fig.12 shows the simplified situation for dissolution oil in the water column and the biological reaction to it. As we can see from the diagramme the dissolution of hydrocarbons is effected by various oceanographic and meteorological variables.

The chemical composition of the oil mainly determines the fraction entering the watercolumn. However, temperature, through it viscosity, spreading and evaporation, enhance or retard dissolution. The whole complex is positively influenced by wind and wave action. The latter will also provide another mode of introduction of oil into the water column: dispersions are formed which can also become persistent emulsions if turbulence energy is high enough, and organic substances, acting as natural emulsifiers, are present.

On the other side, the biological question whether the resulting concentrations exert an effect -- lethal or sublethal -- can only be answered empirically. Here, the first key factor is the sensitivity of a species. Second key factor is the duration of influence. This might change with some other biological variables or might be influenced from the physico-chemical side, e.g. through the change of the concentration gradient. In open sea conditions, as the ARGO MERCHANT spill, it is obvious that hydrocarbon concentrations in water at a given position were subject to permanent change. Other specific difference that result in a variation of influence duration are e.g. coincidence with spawning period, length of incubation time of eggs, length larval period, and also buyancy of eggs and diurnal migrations of larvae.

Biological evaluation

In the following, the situation of the plankton will be taken as an example for similar extrapolations to other ecological communities. As said before, assessment of the biological effect needs at least 3 major informations: hydrocarbons concentrations, residence time in the measured area, and the empirical knowledge of the specific sensitivity.

For cod eggs and young cod larvae this information was provided through a laboratory test. Unfortunately, the ARGO MERCHANT-oil mixture could not be tested itself as it was not available at the time of experiment. Another Venezuelan no. 6-fuel oil from the standard stock of API was used instead.

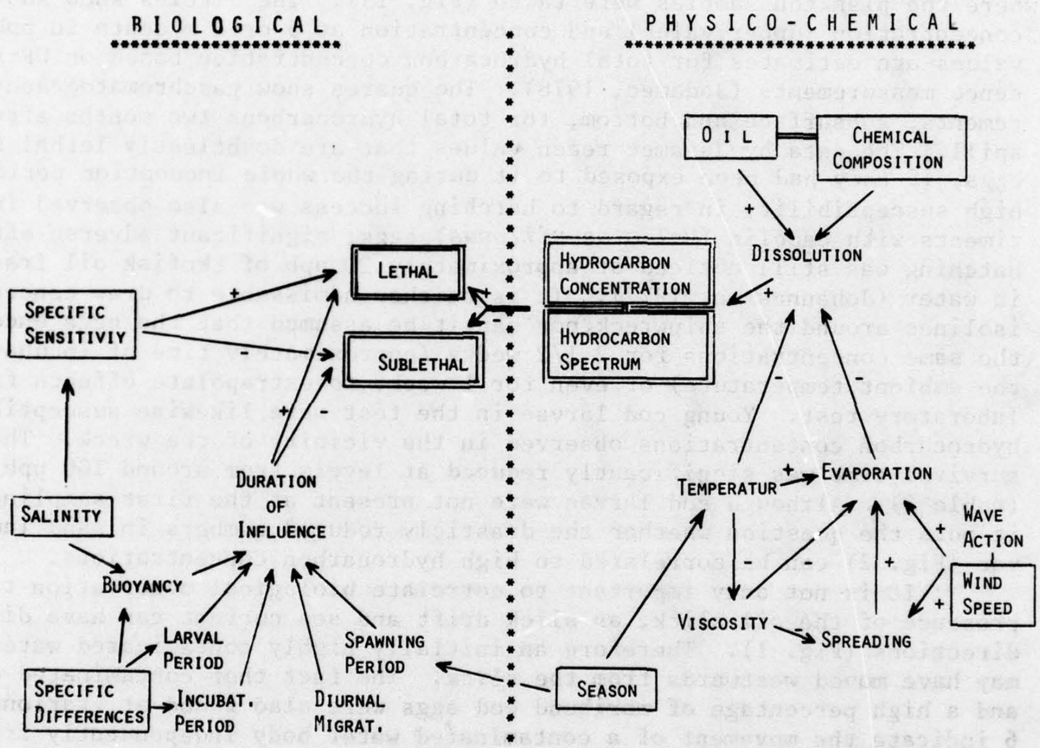

Fig. 12. Physico-chemical and biological factors influencing the overall-effect of an oil spill on pelagic organisms. Expressions in single frames= independent variables, those without frames = dependent variables. Double framed words, hydrocarbon concentration and hydrocarbon spectrum, are focussing points of dependent variables that exert lethal or sublethal toxicity.

Test medium was the sea water extract of the oil, tested at 3 concentrations (Kuhnhold, 1978a). The critical initial concentrations (which were subject to decrease during the static test) are shown in table 2. Eggs exposed half a day after fertilization exhibit 50% viable hatch at only 20-30 ppb of total dissolved hydrocarbons. If exposed from the third day on the critical concentration for viable hatch increases to 30-40 ppb. One week old eggs tolerate 150-200 ppb as initial concentration for 50% viable hatch.

Could eggs in the field have been damaged ? There are data existing on concentrations of total hydrocarbons. The shortcomings, however, are that the data available were from almost the same time but not from stations where the plankton samples were taken (Fig. 13). The circles show sub-surface concentration (upper value) and concentration at 5 or 3 m depth in ppb. These values are estimates for total hydrocarbon concentration based on UF-fluorescence measurements (Jadamec, 1978). The quares show gaschromatography measurements, subsurface and bottom, for total hydrocarbons two months after the spill. The data by Jadamec reach values that are doubtlessly lethal for cod eggs, if they had been exposed to it during the whole incubation period. Similar high susceptibility in regard to hatching success was also observed in experiments with capelin (*Mallotus villosus*) eggs; significant adverse effect on hatching was still noticed at approximately 20 ppb of Ekofisk oil fraction in water (Johannessen, 1977). It is neither admissable to draw concentration isolines around the shipwreck,nor can it be assumed that the eggs encountered the same concentrations for 2 1/2 weeks (approximately time of incubation at the ambient temperature) or even for 1 week, to extrapolate effects from the laboratory test. Young cod larvae in the test were likewise susceptible to hydrocarbon concentrations observed in the vicinity of the wreck. Their survival time was significantly reduced at levels from around 100 ppb up (table 3). Although cod larvae were not present at the first sampling cruise, it puts the question whether the drasticly reduced numbers in sand launce larvae (Fig. 2) can be correlated to high hydrocarbon concentrations.

It is not only important to correlate biological observation to the presence of the oil slick, as slick drift and sea current can have different directions (Fig. 1). Therefore an initially highly contaminated waterbody may have moved westwards from the slick. The fact that contaminated copepods and a high percentage of moribund cod eggs were also found at stations 5 and 6 indicate the movement of a contaminated water body independently from the visible slick movement.

For a better interpretation of the biological findings hydrocarbon analyses should be an absolute MUST along with every biological sample taken. On the other side the low number of samples does not provide a comprehensive picture of the distribution of pelagic organisms to judge the extent of damage of the fish brood population. For the case of fish eggs and larvae also empirical data from other surveys must be taken. The spill did not occur during the peak spawning season of either species represented at the egg stage, and it only covered a minor part of the total cod and pollack spawning area. Assuming lethal effect around the spill site, even at peak spawning season this would result in a low percentage of total egg and larval mortality.

These considerations are equally valid for other groups and communities. During the last past years more and more studies have focussed on the uptake of oil benthic invertebrates as it has become proved that sediments do accumulate hydrocarbons at high rates and that they can retain them -- even unaltered -- for longer time (e.g. Blumer and Sass, 1972; Vandermeulen et al., 1977 and Sanders, 1977). On the other hand has it been observed that animals accumulate single hydrocarbons of the water dissolved fraction of various mineral oils, and that they are able to discharge the chemical burden if exposed again

Table 2: Critical (initial) concentrations for 50% viable hatch of cod larvae

Age of eggs exposed (days at $7^{o}C$)	Total dissolved (CCL_4) hydrocarbons of no. 6 fuel oil (ppb)
0,5	20 - 30
3	30 - 40
7	150 - 200

Table 3: Effect of the Water Soluble Fraction (WSF) of the Venezuelan fuel oil no. 6 on mean survival time of young unfed cod larvae. THC : total hydrocarbons concentration

Age at exposure (days)	Initial concentr. of THC (ppb)	50% mortality after (days)	Time after exposure began (days)	Difference in 50% survival time between control and treated larvae (days)
2	0	13.7	11.7	--
	10	14.1	12.0	+0.4
	100	11.6	9.6	-2.1
	500	9.2	7.2	-4.5
4	0	15.0	11.0	--
	10	16.3	12.3	+1.3
	100	14.0	10.0	-1.0
	500	11.4	7.4	-3.6
8	0	13.4	5.4	--
	10	13.2	5.2	-0.2
	100	12.0	4.0	-1.4
	500	11.5	3.5	-1.9

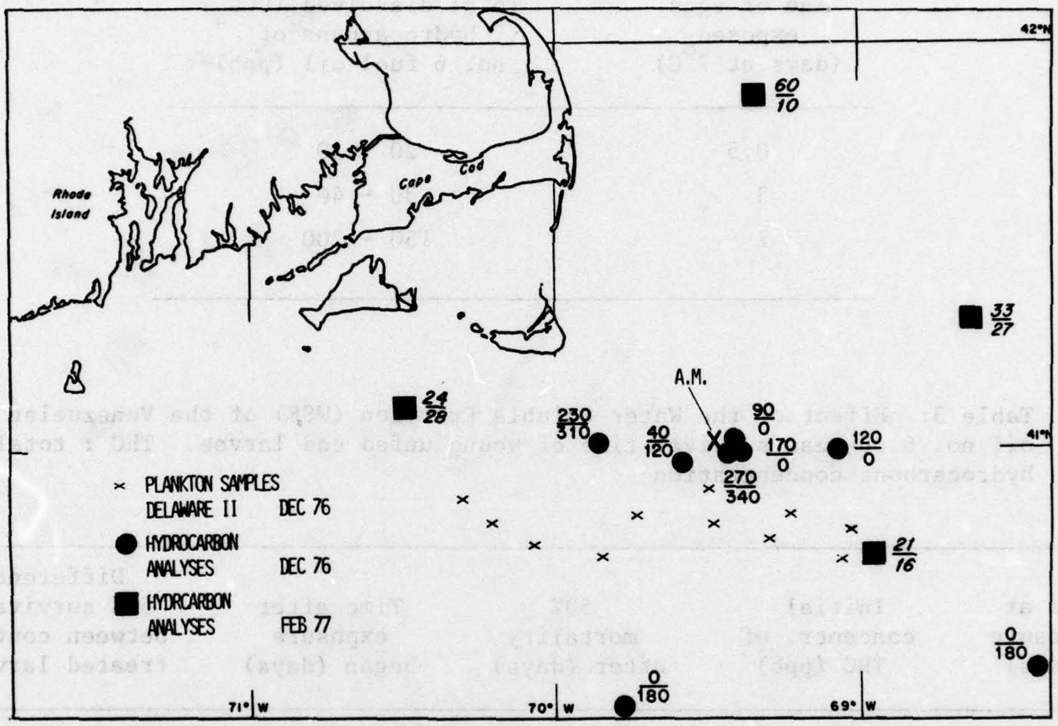

Fig. 13. Diagramme showing locations of some hydrocarbon measurements and plankton sampling. Numbers with circles give values for surface and 3(5)m samples (Jadamec, 1978), those with squares for 3m and 3m off bottom-samples (Boehm et al., 1978).

to clean water (e.g. Stainken, 1977; Stegemann, 1974). This means that low concentration of short-term pollution like a tanker spill are of temporary meaning for the animals only contaminated with polluted water, and even if, as reported above, their physiological conditions like O_2-consumption of gill tissue and characteristic metabolic reactions are impaired.

Although population changes in benthic and pelagic communities have not been noticed, and though prey-predation relationship seemed to have remained the same, the entry of oil into the food chain or web was indicated. Bowmann and Langton (1977) point out two ways of transport possible in the Nantucket/Georges Bank communities (Fig. 14). Sofar the fisheries catch data did not reveal any changes in the fish populations. However, one year after an oil spill can still be regarded as "short-term" for an ecosystem, while the low sublethal concentrations may only reveal after longer intervals. Johnson (1977), critically reviewing studies of sublethal effects in literature, points out that the level in tissues, and the dynamic process determining them, relate more directly to their toxic effect than the concentration in seawater. Unfortunately there is little information relevant to the effects of petroleum on maturation of animals, reproduction and species relationship and it cannot be overemphasized that actually we know very little about the primary sublethal after effects of major spills or chronical oil inputs, much less of their ramifications through eco-webs. The critical sublethal concentrations for the environment are those concentrations which carry with them the *risk* of disrupting or unbalancing important biological processes.

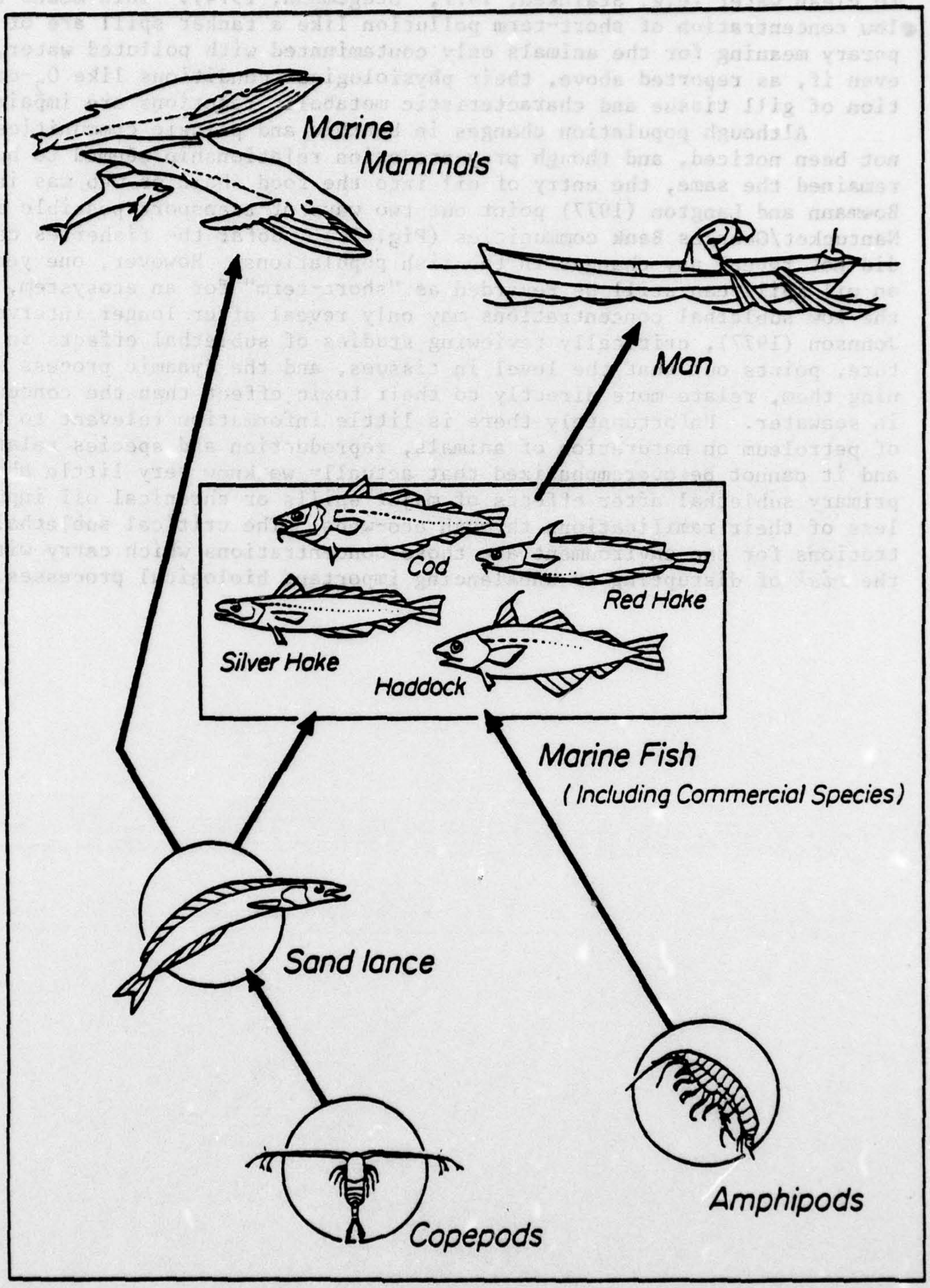

Fig. 14. Possible bathway of oil through food chain from important food organisms that had been found contaminated with oil (from Bowmann and Langton, 1978).

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THE ARGO MERCHANT OIL SPILL: IMPACTS ON BIRDS AND MAMMALS

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of their time on the water and are difficult to identify and count. A number of laboratory studies have been conducted to assess the effects of oil on adult and juvenile birds and eggs (Hartung 1965, 1967; Hartung and Hunt 1966; Albers 1976; Szaro and Albers 1976; Miller et al. 1978). However, little if any information has been gathered about physiological changes due to accidental oiling in marine birds found in the field. Data from bird censuses on Georges Bank in December 1976 and January 1977 and of necropsy findings on five species of beached birds are presented below. Censuses were carried out by Manomet Bird Observatory and necropsies at Boston University.

Impacts of oil on marine mammals are also not well documented. In the rash of spills in recent years (since the TORREY CANYON in 1967), no documented cases of cetaceans being killed by oil have been found (Malins 1977). Reports of seals dying from oil ingestion, coating or suffocation due to coating are also not well documented (Anon. 1970; Morris 1970). Smith and Geraci (1975) and Geraci and Smith (1976) have conducted controlled studies of oil effects on ringed seals (*Phoca hispida*) and harp seals (*Phoca groenlandica*). To date, no studies have been undertaken dealing with effects of oil on cetaceans. Data on marine mammal sightings within two months following the ARGO MERCHANT oil spill are presented below.

METHODS

Marine Birds

Observations of birds were made aboard the USCGC VIGILANT from 15 to 24 December 1976 while the ship was within 3 n.m. of the ARGO MERCHANT wreck site. Speices, abundance, behavior and presence of oil were recorded (Powers and Rumage 1978).

In January 1977, observers aboard four research vessels conducted quantitative observation of pelagic species using the method of acceptable ten-minute watches. This is a count of the total number of each species within sight with the aid of binoculars, when the vessel is moving in a fixed direction at a constant speed of greater than or equal to four knots. Visibility must be greater than 1 km. Bias in this estimation of numbers of birds present may result from unavoidable repeated counts of species such as gulls which commonly follow ships. Species, number, age, behavior, and amount of oiling were recorded where possible (Powers and Rumage 1978).

Beached bird surveys were carried out on Nantucket and Martha's Vineyard from 20 December 1976 to 24 January 1977. Each bird found was numbered, and species, sex, age, and degree of oiling was recorded as well as the date and location where the bird was picked up (Cardoza 1977). Live birds were taken to Felix Neck Audubon Sanctuary on Martha's Vineyard for rehabilitation. Dead birds were frozen for

THE ARGO MERCHANT OIL SPILL: IMPACTS ON BIRDS AND MAMMALS

Barbara Morson

ABSTRACT:

Observations of birds at sea during December 1976 and January 1977 indicated that in the vicinity of the ARGO MERCHANT wreck site a larger percentage of birds were oiled than at other sites on Georges Bank. Of 1121 birds seen from 15 to 24 December, 92% were gulls, approximately 50% of which were oiled.

During beached bird surveys in December and January on Nantucket Island and Martha's Vineyard, 181 birds were collected. Alcids (49%), gulls (27%), and loons (19%) were the most numerous species found. Necropsies on five species of birds revealed that lung and kidney pathology were the most visible signs of damage.

Forty-three sightings of marine mammals were made from 16 December 1976 to 31 January 1977. No oiled mammals were seen.

Research priorities for birds and mammals include baseline population studies, effects of oil on reproductive potential and survivability, and studies on methods of estimating actual impacts to populations.

INTRODUCTION

While it is known that oil spills are, in general, hazardous to many types of marine life, effects of oil on specific species are often difficult to quantify. Oil impacts on marine birds have been documented by a number of authors (Bourne, et al. 1967; Drinkwater et al. 1971; Hope-Jones et al. 1970; Greenwood et al. 1971). Most of these workers have based their estimates of mortality on numbers of birds washing ashore. It is often very difficult, if not impossible, to census oiled birds at sea. Certain species such as gulls and fulmars tend to follow boats for long periods of time, thus giving inflated estimates of their numbers. Other species, particularly the Alcidae, spend most

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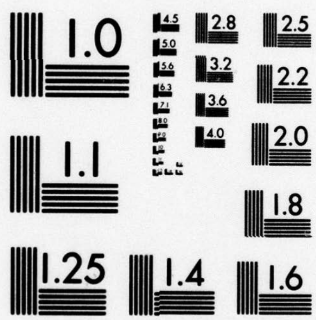

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

necropsies. Necropsies were conducted on 15 specimens, and included the following type of examination (Powers and Rumage 1978):

(1) External examination for degree of oiling and presence of lesions,
(2) Examination of lungs, kidneys, brain and liver for congestion,
(3) Examination of digestive tract for food and parasites,
(4) Examination of other types of respiratory blockage.

Marine Mammals

Between 16 December 1976 and 31 January 1977, aerial surveys for marine mammals were carried out during regular U.S. Coast Guard oil mapping flights. Observations were conducted for the most part in an HU-16E at 500 feet altitude or below, flying at a speed of 145 knots. A grid-line track system was used with flight-lines of varying length ten miles apart. Species, number, locations, and direction of travel were recorded for all marine mammal species seen (Grose and Mattson 1977).

RESULTS

Birds

Observations of birds from the VIGILANT during 15-24 December indicated that about 92% of the birds within 3 n.m. of the wreck were Great Black-backed Gulls (*Larus marinus*), Herring Gulls (*L. argentatus*) and Black-legged Kittiwakes (*Rissa tridactyla*). Other common species present included Gannets (*Morus bassanus*), alcids (Alcidae) and Northern Fulmars (*Fulmarus glacialis*). Daily totals by species are recorded in Table 1; over the day period 1121 birds were seen. The most frequently oiled species recorded were Herring Gulls (59%), Black-backed Gulls (41%), Gannets (12%), and Black-legged Kittiwakes (9%) (Grose and Mattson 1977) (Table 1).

Three cruises in January on Nantucket Shoals and Georges Bank revealed that the largest concentrations of Kittiwakes, Great Black-backed Gulls and Northern Fulmars were north and east of the wreck site (Figures 1-3). Herring Gulls were more concentrated to the south of the wreck site (Figure 4). However, a larger proportion of birds seen near the wreck and in the oil slick track were visibly oiled (Figures 1-4).

Forty-seven unidentified large auks were seen within 40 n.m. of the wreck site. None of the birds were visibly oiled, but as these birds spend most of their time in the water, their underparts may have been oiled and observers were unable to detect this (Powers and Rumage 1978). Of 91 Dovekies seen, 12 were oiled. Most of these birds were sighted in the northeastern portion of Georges Bank.

In beached bird surveys, 173 birds were collected from Nantucket Island and 8 from Martha's Vineyard (Table 2) (Cardoza 1977). Of these, 69 live birds were sent to Felix Neck Audubon Sanctuary on Martha's Vineyard for rehabilitation. Twenty-five birds were eventually released, including 18 murres (*Uria sp.*), 6 Razorbills (*Alea torda*), and one Black-legged Kittiwake (Ben-David, G., pers. comm.). Alcids (49%), gulls (27%), and loons (*Garia sp.*) (19%) were the most prevalent species washed ashore.

Necropsies were performed on 15 of the birds which washed ashore. Results of the necropsies indicated that all birds were underweight with little body fat and no food in the digestive tract (Powers and Rumage 1978). The pathology findings are summarized in Table 3 and are similar to those found in waterfowl exposed to oil (Hartung and Hunt 1966). Lung hemorrhages were found in seven birds and lipid pneumonia in two. Blockage of the Bowman's capsule by cellular debris and precipitation of urates in the kidney tubules was also seen (Powers and Rumage 1978). This renal blockage resulted in an inability of the bird to filter waste products, resulting in uremic poisoning. Again, these findings match those of Hartung and Hunt (1966).

One Common Murre (*Uria aalge*), with only traces of oil on its plumage, was found to have a chronic infestation of unidentified parasitic flukes in the kidney and digestive tract.

Marine Mammals

Forty-three separate sightings of marine mammals were made between 16 December 1976 and 31 January 1977. Species sighted included 21 finbacks (*Baleanoptera physalus*), 7 white-sided dolphins (*Lagenorhynchus acutus*), 13-15 pilot whales (*Globicephala malaena*), two unidentified rorquals and possibly one gray seal (*Halichoerus grypus*). There did not appear to be any bias in distribution of these animals in relation to the oil. Only on one occasion were whales seen in the vicinity of heavy oil concentrations; these animals did not appear stressed nor were they in direct contact with the oil. No increase in strandings were seen (Grose and Mattson 1977).

DISCUSSION

Assessment of impact on sea birds due to oiling cannot be complete with beached bird surveys. Observations at sea provide the scientist with a much more realistic picture of the species and numbers affected (Powers and Rumage 1978). Many truly pelagic species will not come ashore unless they are severely oiled and are near shore to begin with (Bourne 1968). Most seem to die at sea, either from loss of water repellancy of the plumage, starvation, or some type of internal pathology (Malins 1977). In the case of the ARGO MERCHANT, the prevail-

ing off-shore winds and currents (Grose and Mattson 1977) would have promoted a seaward drift of any affected birds.

Powers and Rumage (1978) note that there is a discrepancy between beach surveys and sea observations in relation to most numerous oiled species seen. Alcids appeared most often on shore, while oiled gulls were seen most commonly at sea. There are several reasons for this. First, alcids are very difficult to observe at sea. Because they spend most of the time on the water and are extremely wary, it is difficult to observe the birds to determine the amount of oiling. Secondly, recent research (Staunton, P. 1976, pers. comm.) indicates that gulls may be able to withstand oiling better than other types of sea birds. Thirdly, diving birds such as alcids are much more vulnerable to oiling than birds which spend most of their time in the air. Thus, a larger percentage of alcids may have become oiled. Fourthly, during the winter of 1976, alcids were seen in unprecedented numbers near shore along the Massachusetts coast. All alcids seen were within 40 km of the wreck site, while most of the gulls seen were associated with fishing vessels on the northeastern portion of George's Bank and probably flying to Nova Scotia to roost rather than the Massachusetts coast.

From beached bird surveys, it was found that most birds were oiled on the breast, belly and sides, indicating that they had come into contact with the oil while resting on the water (Cardoza 1977). Oiling on the back of some of the diving birds would have indicated that these birds had come into contact with oil when returning to the surface following a dive. Lung hemorrhages in the birds examined indicated that oil could have entered via accidental inhalation or leakage through the glottis during preening (Powers and Rumage 1978). Lodging of oil particles in the parabronchi and subsequent blockage due to the immigration of white blood cells to combat the foreign substance could have caused the hemorrhaging. Kidney damage seen could have been due directly to oil or to dehydration from lack of food (Powers and Rumage 1978). Pathological effects of oil on birds have been investigated by Hartung and Hunt (1966), Snyder et al. (1973) and others. Snyder et al.'s (1973) study of oiled birds from the 1971 San Francisco Bay spill indicated severe damage to kidneys, intestinal tract and liver. Hartung and Hunt (1966) have studied both wild oiled birds and experimentally oiled birds in the laboratory and have noted a high incidence of lipid pneumonia and toxic nephrosis as well as changes in the pathology of the pancreas. These results match those of Powers and Rumage (1978) from birds oiled by ARGO MERCHANT oil.

The paucity of marine mammal sightings only serves to point out the difficulty in censusing these animals and determining the impact of oil on them. To date there have been no confirmed deaths of cetaceans due to oiling from any spill. It is often difficult to relate cause and effect in these cases, because oiling may not be the direct cause of death but only a stimulator for various kinds of complications to set in. The ARGO MERCHANT spill probably occurred during a fortunate time, because later in the season whales migrating to their summer feeding grounds would have had a higher probability of contacting the oil.

Assessment of impacts on both marine birds and mammals is difficult because of the lack of a good baseline from which to assess changes in populations or physiology. Populations studies of marine birds and mammals have not been well developed in the western Atlantic. Work in the British Isles (Clark 1968) has indicated that unless very drastic numbers of birds are killed, oil seems to have little effect on populations. However, only in the past few years has there been an effort to collect data on changes in reproductive potential of various species due to oil. The potential effects of oil on species with low reproductive potential, such as alcids, could be disastrous. Another unstudied aspect of oil effects is the impact of oiling on long-term survivability of individuals. Can sublethal doses of oil cause complications which affect the ability of a bird to live and grow? A number of studies have begun to approach this problem. Holmes and Cronshaw (1977) have been working with several species of water fowl to determine the effects of daily doses of oil in the diet. They have tested the effects of oil on hatchability of eggs, as have Szaro and Albers (1976) and Hartung (1965).

Finally some good methods of estimating actual impacts of oil on populations of birds and mammals must be found. Long term monitoring of breeding colonies with careful observations of mortality and oiling would be one method, but is difficult to carry out on a large scale. Clark (1968) notes that estimates of actual mortality from spills is up to ten times the number of birds which wash ahore. Pelagic species such as auks do not come ashore unless severely oiled. Many simply sink if their plumage becomes waterlogged; this may cause differential loss according to species. Fish may also account for some loss of birds at sea (Glegg 1945). Experimental data are needed to gain a better understanding of these types of losses.

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Table 1. Daily seabird totals and percent oiled birds at ARGO MERCHANT wreck site 15-24 December 1976 (total%) (Grose and Mattson 1977).

Species	15	16	17	18	19	20	21	22	23	24
	Date (December 1976)									
Herring Gull	136/0	15/0	42/some	89/many	11/most	7/most	180/70	68/17	40/75	18/67
Black-backed Gull	14/0	1/0	13/some	3/many	2/?	2/?	45/20	24/40	23/48	32/100
Black-legged Kittiwake	37/0	24/0	33/?	44/?	43/few	17/few	28/4	18/6	12/17	8/25
Gannet	37/0	2/0	6/?	7/?	1/?	1/?	7/28	6/0	1/0	2/?
Thick-billed Murre	2/0	0	4/?	0	0	1/?	0	0	0	0
Northern Fulmar	2/0	0	0	1/?	0	0	0	2/0	0	0
Skua	1/0	1/0	0	0	0	0	0	1/0	0	0
Razorbill	0	0	0	0	0	0	0	2/0	0	0
Glaucous Gull	0	0	0	0	0	0	0	1/0	0	0
Iceland Gull	0	0	0	0	0	0	0	0	1/?	0
Greater Scaup	0	0	0	0	0	0	0	1/?	0	0
Common Eider	0	0	0	0	0	0	1/?	0	0	0
Red-breasted Merganser	0	0	0	0	0	0	0	1/?	0	0

Table 2. Numbers of birds, by species, collected from beaches at Nantucket Island and Martha's Vineyard, 20 December 1976 to 24 January 1977. (From Powers and Rumage 1978)

Species	Live	Dead	Total	Percent of Total
Common Murre	32	17	49	27
Common Loon	11	21	32	18
Great Black-backed Gull	2	29	31	17
Razorbill	16	10	26	14
Herring Gull		15	15	8
Thick-billed Murre	3	7	10	6
Common Eider	2	3	5	3
Red-throated Loon		1	1	1
Gannet	1	1	2	1
Grebe sp.		1	1	1
Double-crested Cormorant		1	1	1
Cormorant sp.	1		1	1
White-winged Scoter		1	1	1
Common Scoter		1	1	1
Bonaparte's Gull		1	1	1
Black-legged Kittiwake	1	1	2	1
Murre sp.		1	1	1
Dovekie		1	1	1
	69	112	181	

Table 3. Summary of pathology findings on 15 beached birds, Nantucket, Massachusetts. December, 1976 (from Powers and Rumage 1978).

Species	Sample Size	Number of Specimens with: Hemmor-rhagic Lungs	Pneu-monia	Kidney Blockage	Kidney/Lung Congestion	Parasites (Chronic)
Common Loon	5	2	1	2	0	0
Great Blackbacked Gull	2	2	0	0	0	0
Herring Gull	3	2	0	0	1	0
Common Murre	4	1	0	1	1	1
Thick-billed Murre	1	0	1	0	0	0

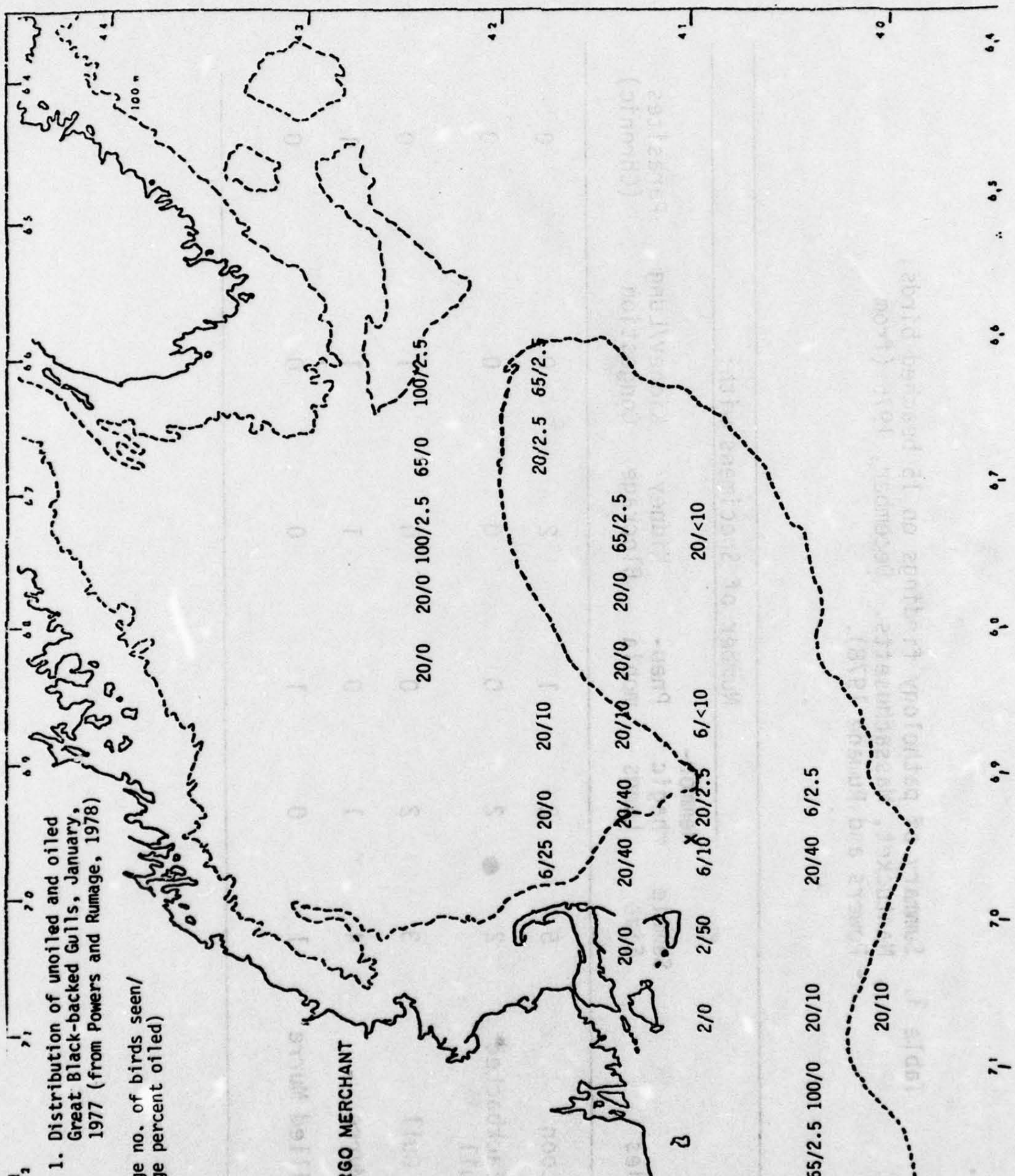

Figure 1. Distribution of unoiled and oiled Great Black-backed Gulls, January, 1977 (from Powers and Rumage, 1978)

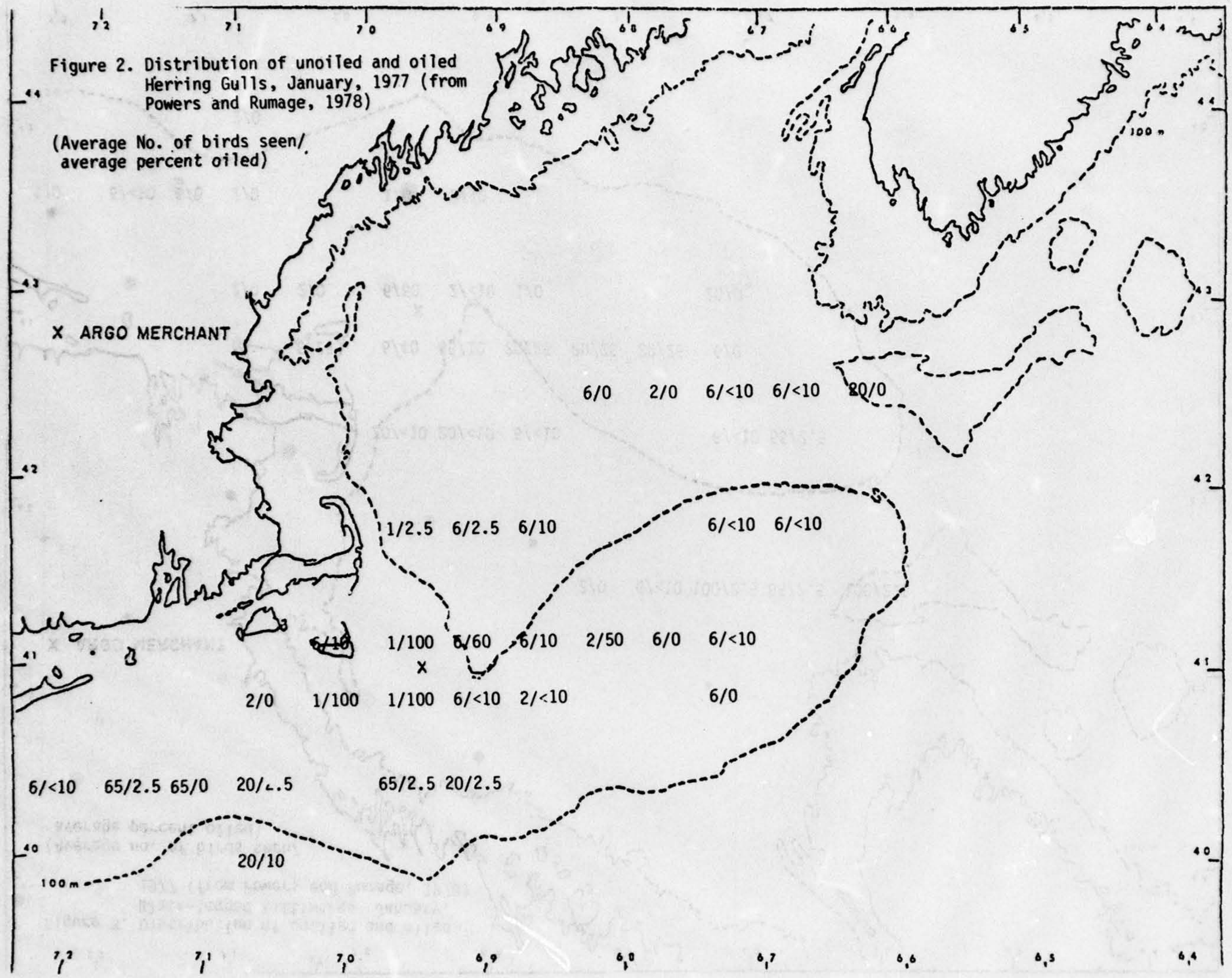

Figure 2. Distribution of unoiled and oiled Herring Gulls, January, 1977 (from Powers and Rumage, 1978)

(Average No. of birds seen/ average percent oiled)

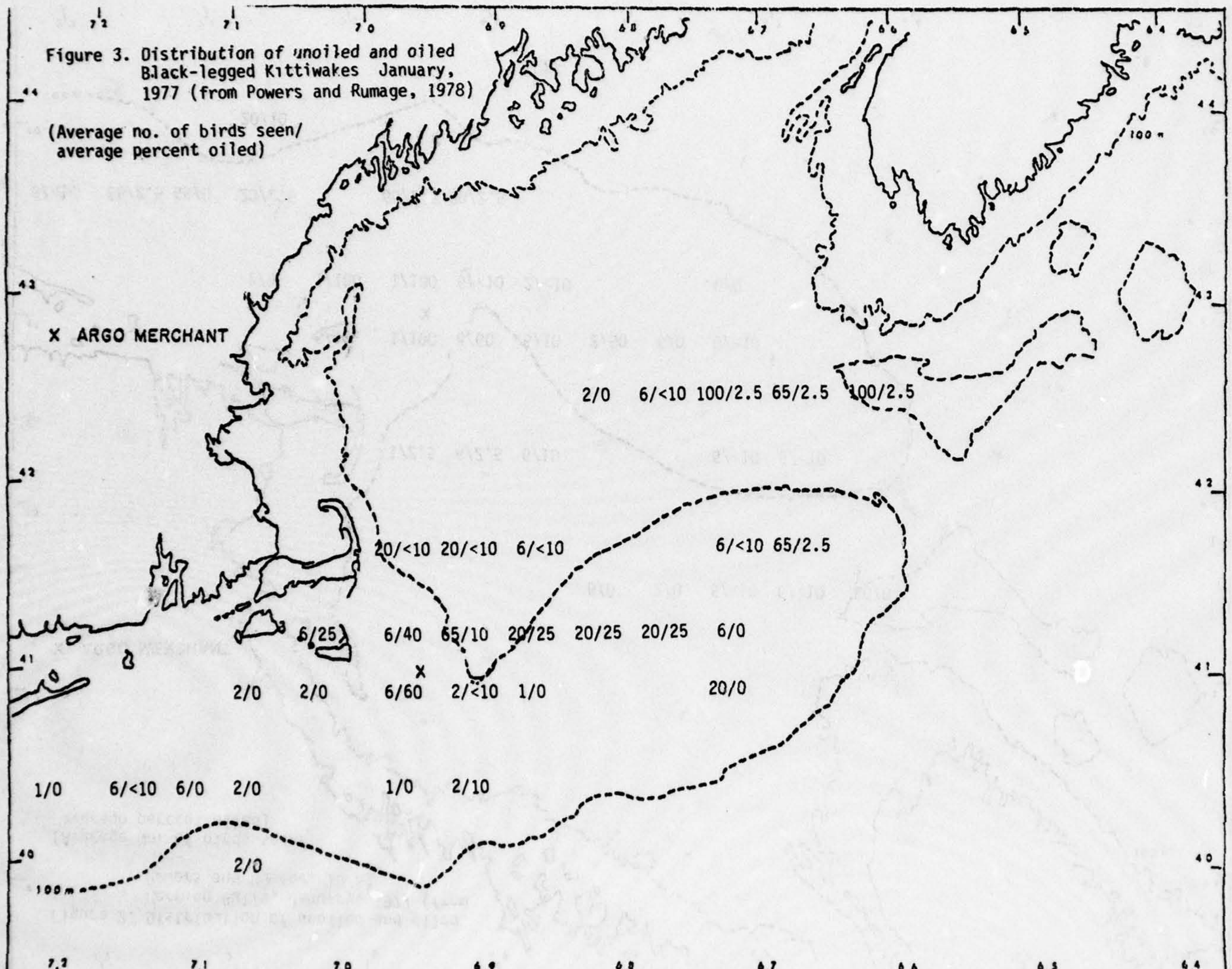

Figure 3. Distribution of unoiled and oiled Black-legged Kittiwakes January, 1977 (from Powers and Rumage, 1978)

(Average no. of birds seen/ average percent oiled)

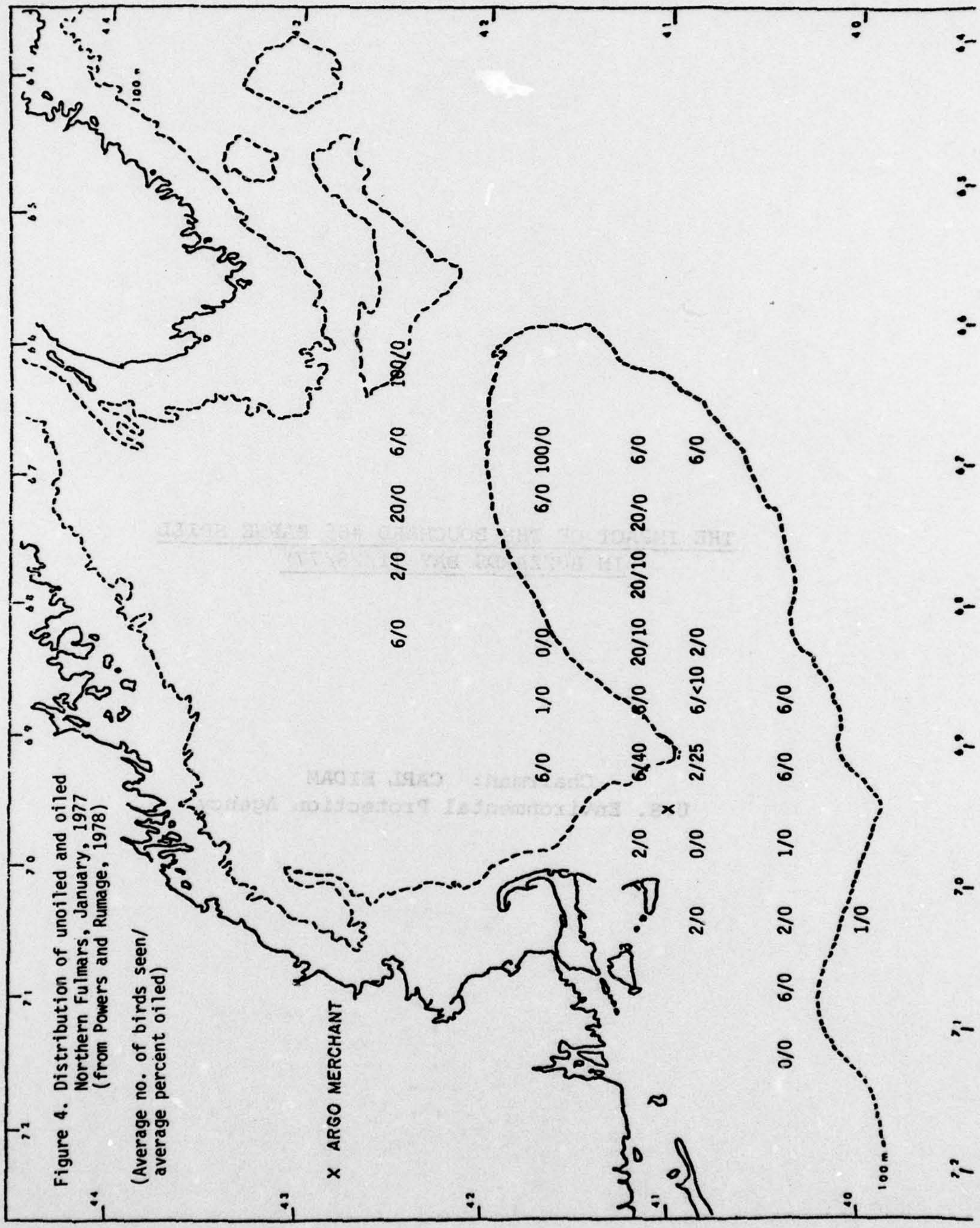

Figure 4. Distribution of unoiled and oiled Northern Fulmars, January, 1977 (from Powers and Rumage, 1978)

(Average no. of birds seen/ average percent oiled)

THE IMPACT OF THE BOUCHARD #65 BARGE SPILL IN BUZZARDS BAY (1/28/77)

Chairman: CARL EIDAM
U.S. Environmental Protection Agency

OIL SPILL BEHAVIOR IN ICE
DURING THE 1977 BUZZARDS BAY OIL SPILL

by

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ABSTRACT

On January 28, 1977, the barge BOUCHARD #65 grounded, releasing approximately 81,150 gallons of No. 2 home heating oil into Buzzards Bay, which was 90% ice covered. Field measurements and observations were initiated at the spill site on January 29, and continued until February 25, when only negligible amounts of oil remained in the bay. This paper documents these findings and puts these results in perspective with the present state-of-the-art of oil spill behavior in ice-infested waters.

Most of the present data on oil pollution in ice-covered waters has been obtained from spills in static ice conditions. The Buzzards Bay spill, which occurred in moving ice, therefore merited special attention. Of particular interest was the initial transport of the oil under the ice, its concentration in the rafted ice, the interaction of the oil with the hummocks and pressure ridges, its spreading from concentrated pools on the surface of ice floes, its penetration into the snow and ice, the weathering of the oil, and its final transport by ice floes during breakup.

With rising interest in petroleum reserves located in cold regions, the application of the Buzzards Bay experience to other geographical areas could be useful. However, there are limitations which must be considered when applying this experience to other cold regions, such as coastal Alaskan waters. By continuing to respond with study teams to "spills of opportunity" in cold regions, knowledge of the behavior of oil spilled in these regions can be substantially improved, and our ability to properly prepare effective countermeasures will be greatly enhanced.

ENVIRONMENTAL SETTING

Buzzards Bay, located on the Massachusetts coast (Figure 1) is a shallow, nonestuarine bay, approximately 46 km long and 19 km wide, with an average depth of 11 m. Connecting Buzzards Bay with Cope Cod Bay to the north is the man-made Cape Cod Canal (Figure 2). The winter of 1977 was unusually severe for most of the northeastern United States with unusual

icing conditions reported for many parts of the New England coast from December through February. Buzzards Bay which normally does not ice over, was 90% covered by January 28.

The ice which grew was less saline than normal sea ice primarily because the ice had gone through four periods of above-freezing temperatures and rain which lowered the salt content of the ice. This low-saline ice was not as porous or elastic as normal first year sea ice.

Several types of sea ice formations were found in Buzzards Bay. Shorefast ice, with a characteristic thickness of 0.3 m covered the waters of the protected coves. This flat, smooth shorefast ice covered Megansett Harbor, Phinneys Harbor, the area between Scraggy Neck and Wings Neck, and the area from Wings Cove east to Tobys Island (Figure 2). Small tidal and thermal cracks occurred in this ice, but it was otherwise undisturbed. In the areas not protected by the shoreline, the wind stresses and tidal currents, 0.5 ms^{-1} at approximately six-hour intervals, caused the formation of an active ice zone characterized by broken ice formations (Figure 3). In this area between the channel and the shorefast ice zone, the ice consisted of large floes separated by hummocks, pressure ridges, rafted ice, and leads. These floes typically measured 50 m across and had a thickness of 0.4 m. In the ship channel, the movement of the ships broke the ice into small floes, which then rafted and ridged, resulting in ice with a thickness of 1 m.

An overall view of Buzzards Bay from Cleveland Ledge to Cape Cod Canal on the day of the spill revealed that 50% of the area was covered with shorefast ice and 50% was an active ice zone. The active ice zone region consisted of 75% ice floes and 25% hummocks, pressure ridges, and rafted ice. Ice conditions of this type are more typically seen in the higher latitudes of the Canadian and Alaskan sub-arctic, such as the Gulf of St. Lawrence, rather than in the warmer waters of Buzzards Bay.

CHRONOLOGY OF SPILL INCIDENT

On the afternoon of January 28, 1977, the barge BOUCHARD #65 was grounded while attempting to make headway northeast through the ice-covered waters of Buzzards Bay, with a cargo of 3.2 million gallons of No. 2 home-heating oil. Two thirds of the way up the bay near Cleveland Ledge Light, the barge was beset in the ice. While the attending tug disengaged itself to break ice, wind and ice pressure forced the BOUCHARD #65 off course. At approximately 1800 hours, the barge struck Cleveland Ledge and holed four of her seven tanks.

During the night, the barge was towed 6.9 km to Wings Neck, spilling oil into its track of broken ice. In an attempt to plug the holes and to prevent sinking, the barge was intentionally grounded on the hard, sandy bottom 300 m west of Wings Neck where offloading onto a second barge began. Oil continued to leak into the waters off Wings Neck during the remainder of the day. Approximately 80% of the oil spilled occurred at this location.

Due to the severe ice conditions, the BOUCHARD #65 was moved to the Massachusetts Maritime Academy docks on the afternoon of January 29. The barge did not leak any appreciable amounts of oil after being towed from Wings Neck. Final measurements made by the Bouchard Transportation Corporation indicated that a total of 81,150 gallons of No. 2 oil were spilled.

PROGRESSION OF THE SPILLED OIL

Spilled oil from the ruptured barge was initially transported into the fractured ice formations and upon breakup was distributed throughout Cape Cod. A description of this overall oil distribution from its release and the subsequent periods of different oil, ice, and snow interactions is provided. This overview is followed by a discussion of the specific data and observations made at the spill.

The No. 2 home-heating oil spilled from the BOUCHARD #65 was released in essentially three areas: 1) off Cleavland Ledge, where the barge originally grounded; 2) along the path of broken ice made by the barge and accompanying tug when being towed from Cleveland Ledge to Wings Neck; and 3) at Wings Neck where offloading operations were attempted. Approximately 4,000 gallons were found near Cleveland East Ledge. This oil was contained in an area of 2,800 m^2. The second spill area was found along a 6.9 km track created as the barge was towed from Cleveland Ledge to Wings Neck. This oil was incorporated into hummocks and ridges as the track closed. The majority of the oil was spilled in the third area off Wings Neck. The interaction between the tidal currents and the broken ice determined the distribution of the oil in this area.

These tidal currents swept the oil from Wings Neck in a northeasterly direction and distributed in an irregular line to Mashnee Island, a distance of 4.3 km. The major concentration of oil was found between Wings Neck Tower and Wings Neck Cove. Small quantities were also transported both northwest and southwest of the grounded barge. This oil settled into the openings of the various ice formations. This transport process was complete by the second day after the spill, and from that time to the breakup of the ice, the oil remained relatively stable in a 0.1 km^2 area.

Following the initial distribution of the oil, the spill can be discussed in terms of three time periods. During the first period, January 29 to February 5, the oil remained stable in the ice and since the weather remained cold and clear, the oil was clearly visible from the air. The second period, February 5 to February 10, began with a snow storm and was followed by relatively warm weather. The snow saturated the oil on the surface and hid much of it from aerial view. The warm weather weakened the ice and oil sheen was occasionally found in the open water areas. During the third period, February 10 to February 26, the oiled ice at Wings Neck began to break up and oily floes began to move around the Bay and through the canal. Sheen was observed at this time throughout the open waters of Buzzards Bay, up through the canal and in Cape Cod Bay. Large oily ice floes and ice chunks traveled up through the canal into Cape Cod Bay. Based upon aerial observations, the visible oil sheen was finally distributed over an area of 19.4 km^2 in the coves and bays throughout Cape Cod.

OIL TRANSPORT UNDER ICE

Under-ice oil transport primarily occurred at Wings Neck. Observers on the leaking barge at Wings Neck stated that after the oil was released from the barge, it built up along the edge of the ice surrounding the barge and was forced under the ice by the tidal currents of $0.5\ ms^{-1}$ and winds averaging $12\ ms^{-1}$. Once under the ice, the currents transported the oil laterally into the fractured ice formations consisting of ice rafts, ridges, and hummocks.

The ice edge surrounding the leaking barge and the ice edge of open water leads did not contain the oil at Buzzards Bay. However, the oil was later contained in the fractured ice formations. It should be noted that there has been several cold region spills where the ice edge contained the oil and served as an effective barrier against spreading (Ramseier et al. 1973, NORCOR 1974, Task Force 1970, Lamp'l 1973). At Buzzards Bay, once the oil was under the ice the water currents were the most important conditions in the spreading of the No. 2 oil. When currents exceed a certain threshold velocity, the oil can be swept along the under-ice surface. Experiments (Uzuner et al. 1975) have shown that the threshold current velocity for transporting No. 2 oil under smooth ice is $0.035\ ms^{-1}$. The water velocities at the spill site were over ten times the threshold velocity. Because of the lack of change in the appearance of the spill one to two days following the release of the oil, it appears that most of the under-ice transport took place within this period followed by its settling into the openings of the fractured ice. The magnitude of the current required to move the oil beneath the ice for different conditions of under-ice surface roughness and for different discontinuous ice features has not been determined.

OIL POOLS IN RAFTED ICE

Approximately 30% of the spilled oil was contained in "deep pools" on the ice surface with depths of about 0.12 m which were formed by rafted ice. The rafted ice resulted from stresses generated by wind, currents, and ship traffic causing ice floes in the active ice zone to slide on top of each other. Their formation resulted in the natural containment of pure oil in quantity soon after the spill.

Oil which flowed from the barge under the ice encountered several rafted floes. The sequence of sketches in Figure 4 shows a possible oil capture scenario. As the current carried the oil under the ice, the oil encountered the bottom of the rafted formations, and would collect and be sheltered from the current in the lee of the submerged part of the raft. The buoyant oil would then rise through an opening between the two ice sheets to replace the heavier sea water in the pond. Once on the surface, the oil was protected from the currents. As the tidal current oscillated back and forth, the fuel which was not protected from the currents would then be swept away.

Estimates made at the spill site suggested that a typical pool measured 0.1 m deep by 2 m wide by 4 m in length with an oil volume of $0.8\ m^3$ (200 gallons). There also were some very large pools which contained as much

as 1,000 to 2,000 gallons (Figure 5). The containment of the oil in these pools made direct suction by hoses into vacuum trucks an encouraging recovery possibility. The Buzzards Bay spill was the first reported incident which occurred in an active ice field with substantial water currents and the formation of these rafted oil pools had been previously unreported.

INCORPORATION OF OIL IN PRESSURE RIDGES AND HUMMOCKS

Pressure ridges and hummocks in the active ice zone at Buzzards Bay also served as effective containment mechanisms for the spilled oil. Oil entrapment in ridges and hummocks occurred along the ship track between Cleveland Ledge and Wings Neck, and off Wings Neck.

In general, oil interacts with pressure ridges and hummocks in two ways. The first occurs when oil is incorporated during the formation of the pressure ridge or hummock. This happens when small contaminated ice pieces are compressed together into a pressure ridge or hummock creating a pile of oiled ice pieces or when oil in a lead along the ice edge is squeezed and coats the ridge walls during the formation of the pressure ridge or hummock.

Secondly, oil can flow into previously formed pressure ridges and hummocks, as shown in Figure 6. The porous pressure ridges and hummocks create numerous small crack systems for the oil to fill in hydrostatically, thus allowing the oil to coat the ice and settle within the crack systems. The keel can also provide a means for containment of oil (Moir et al. 1975). It appears that the oil containment of a ridge or hummock depends upon the water currents, oil properties, ice properties, and porosity and shape of the ridge or hummock.

Throughout the active ice zone in Buzzards Bay, ridges and hummocks comprised approximately 15% of the surface area. These ridges and hummocks extended up to 1 km in length, with widths ranging from 1 to 10 m and a maximum sail height of 1 m. Most of the oil entrapped in the ice ridges appeared to have prentrated into the broken ice pieces with little pooling observed. In many cases, the hummocks, being more porous than the ridges, allowed some heavier concentrations of oil to form, making oil cleanup by direct suction feasible in some instances. However, oil pooling in hummocks was not as extensive as that observed in the rafted ice.

SPREADING OF OIL ON TOP OF ICE

An important effect of the openings between the ice floes and deformed ice was to expose the oil under the ice to the surface. Once in pools, some of the oil was spread in a thin layer onto the ice floe surface. The major spreading mechanism appeared to be the wind blowing the oil directly from the concentrated areas. Several factors were present which encouraged this behavior. Throughout Buzzards Bay, the ice floes had a smooth surface and a low porosity. The oil had a low viscosity and the wind velocities were rather substantial, reaching 15 ms^{-1} on January 29. Also, the

rafted ice configuration consisted of a gradual rise from oil pools to the ice surface presenting little resistance to oil spreading on top of the ice.

It was estimated that approximately 6,000 gallons of oil spread onto the ice surface in this manner. Once on the surface, the oil penetrated 2.5 to 6 mm into the ice under a thin surface coating of oil. Prior to the snowfall, it was observed that the surface oil absorbed solar energy and melted a thin layer of ice beneath it. The No. 2 oil, thinly spread over the ice, was constantly exposed to the wind resulting in some of the more severely weathered oil samples taken at the spill. Similar observations of oil spreading across the ice surface were made during the Deception Bay oil spill (Ramseier et al. 1973).

OIL MIGRATION INTO ICE

The Buzzards Bay ice, with an average thickness of about 0.3 m, was considerably different from Arctic sea ice in terms of its salinity, hardness, and porosity. An ice salinity profile showed that the ice had a low overall salinity. The surface salinity was nearly fresh, with the interior salinity constant at about 4 parts per thousand. For comparison, the surface salinity of winter Arctic sea ice is 20 to 40 parts per thousand and the interior salinity is about 8 parts per thousand. The Buzzards Bay ice, therefore, was a hybrid of lake and sea ice. It grew from water slightly less saline than sea water, and due to the thermal diurnal temperature cycle and rain which tended to wash the salt out of the ice, the resulting ice had the hardness and impermeability of lake ice.

Samples taken throughout Buzzards Bay revealed varying degrees of oil absorption into the ice. A brief description of what was observed and noted by field investigators follows:

1. Oil mixed with slush ice resulted in a 30% volume concentration of No. 2 oil.

2. Heavily stained ice appeared dark yellow and was typically found amidst brash ice and small ice pieces. Oil penetration typically reached a depth of 25 to 60 mm into the ice, resulting in a 3% to 5% oil concentration by volume.

3. Medium stained ice was clearly stained with oil, but was lighter in color than the heavily stained ice. Oil penetration was typically 25 to 60 mm and reached a concentration of 1 to 3% oil by volume.

4. Lightly stained ice showed an oil penetration of between 25 to 60 mm into the ice surface. This surface layer was approximately 0.5% oil by volume.

5. Windblown oil found on top of the ice had, on the average, penetrated 3 mm into the ice; 50% of this penetrated layer was oil.

6. Ice in the affected shorefast and active ice zones had the smell of No. 2 oil on the bottom of the ice. When holding a piece of the ice up to the light, a sheen could be detected on the underside surface. Chemical analysis revealed oil concentrations averaging 310 ppb for the bottom 80 mm.

From these observations it appears that the migration of oil into ice is primarily dependent upon the ice porosity, oil viscosity and surface tension, volume of oil in contact with the ice, and the duration of oil exposure to the ice. The oil spilt in Buzzards Bay had low viscosity and surface tension and the ice was not very porous. In the 1977 ETHEL H spill in the Hudson, the No. 6 oil had a high viscosity and surface tension and the oil tended to adhere to the nonporous ice. In field experiments (Glaeser et al. 1971), Prudhoe Bay crude oil was spilled on a porous ice surface consisting of a layer of recrystalized ice approximately 50 mm thick. This ice was found to absorb oil up to 25% of its volume. Oil can also migrate into the brime channel network of sea ice and it was found (Martin 1977) that the amount of oil trapped within the ice was in the range between 1 and 5% by volume.

OIL ABSORPTION BY SNOW

On February 5, seven days after the spill incident, 12 cm of snow fell in Buzzards Bay. The snow completely covered areas where there was little oil concentration; areas that had heavy concentrations of oil, such as the rafted pools, were saturated with the snow forming an oil/snow mulch. This slush-like mixture was determined to be approximately 30% oil by volume, based on several independent measurements, and could be picked up by hand without any oil dripping free. In addition, oiled ice, which was covered by snow with no oil absorption, formed an ice/oil/ice sandwich. The snow which was oil saturated began to melt much earlier than the surrounding uncontaminated areas due to the solar albedo. In general, the effect of snow greatly hindered cleanup procedures, restricted aerial observation, and forced scientists to redirect their research effort.

Much of the present knowledge of the interaction of oil with snow is contained in six reports (McMinn 1972, Chen 1973, Mackay et al. 1974, Mackay 1975, Task Force 1970, Mackay et al. 1974). In general it was concluded that when oil and snow interact they mix together. The major controlling factors which determine how the oil and snow mix are oil viscosity, snow porosity, snow crystal structure, and temperature differences between the oil and snow. If the oil has a low viscosity and the snow is not heavily packed, the oil can be absorbed quickly and to a considerable depth into the snow. High viscosity oils have a lesser tendency to be absorbed into the snow. Snow that is heavily packed has a reduced absorption capability. There may even be conditions under which snow is essentially impermeable to the spilled oil.

TRANSPORT OF OIL BY ICE FLOES

Beginning about February 8, ice floes as large as 75 m in diameter began to float freely in the open water of Buzzards Bay and break up into smaller floes. By February 9, oiled ice floes were observed in the canal, and by February 10, in Cape Cod Bay. The oil, absorbed in the ice and snow, incorporated in hummocks and pressure ridges, and pooled in the rafted ice formations was transported by these floes. It remained in the ice until melting or further breakup provided a means for release. The oil would then stream from the floes in the form of sheen (Figure 7). This movement of oiled floes continued until February 26 when only a negligible amount of oil was visible in Buzzards Bay.

The contaminated ice floes which drifted into coves settled on the beaches and leached the oil into the sediments and beach grasses. The oil absorbed into this ice was not significantly weathered, therefore, many of its components were still present. The beached ice slowly released this relatively fresh oil, possibly increasing the environmental impact on those areas.

During the ETHEL H spill on the Hudson River (Deslauriers 1977) No. 6 oil interacted with a broken ice field. As these ice floes traveled down the river, it was observed that the heavy tarry oil adhered to many of the floes. The oil which adhered to the ice caused melt holes to form in the ice surface during the warming periods due to the albedo differences. As the oil coated ice floes went into the more open waters, the floes similar to Buzzards Bay released oil in the form of sheen.

WEATHERING OF OIL UNDER VARYING FIELD CONDITIONS

In Buzzards Bay, the No. 2 home heating oil was distributed in various snow and ice formations. The variation in field conditions resulted in the oil being exposed to different temperatures and amounts of air. Samples from these formations were taken on the twelfth day after the spill incident. Chemical analyses on the original cargo and the weathered samples were conducted by the NOAA/National Marine Fisheries Service (NMFS). It was concluded from the weathered oil samples that the saturated hydrocarbons consisting of alkanes represented over 80% of the oil, and the aromatic hydrocarbons consisting of arenes represented under 20% of the cargo. The analyses on the weathered oil samples are provided in Table 1; a description of the sample location, field conditions, percentage loss of alkanes, percentage loss of arenes, and approximated total losses are provided. It was found that evaporation was confined to the more volitile $C_{16}H_{32}$. The relative loss expressed in percentage volume loss was the greatest for oiled ice that was rotated up into the air and was the least for oil underneath the ice along rafts. It was also observed, even in the case of heavy weathering, that the oil did not sink in the water column.

From the various degrees of weathering found at Buzzards Bay, it becomes evident that the media upon which oil is spilled is very important, particularly in cold regions. This result appears to be comparable with other cold regions oil spills (Ramsier et al. 1974, McMinn 1972, Adams 1975, NORCOR 1974, Chen 1973). In addition, all spills showed a substantial reduction in the aging rate when compared to warm climate spills. This could be accounted for by the ice and snow shielding the oil from the wind. Also the cold temperatures could effect oil properties and vapor pressures. While these studies show that broad variations in weathering can exist and is much slower than warmer climate spills, no systematic studies of weathering in cold regions have been performed.

OIL MASS BALANCE

A more complete understanding of the mechanisms surrounding the transport of oil in ice covered waters requires an analysis of the mass balance of the spilled oil. This leads to a quantitative overview of the types of oil/ice involvement. The oil mass balance for Buzzards Bay was constructed for aerial photo mosaics from January 31 to February 5, prior to the snowfall. During this time period, the oil remained stable within the active ice zone. These aerial mosaics were combined with lower altitude and ground level photographs to compile the best possible description of the oil's involvement with the ice. These photographic records were cross-referenced with field samples to determine the percent and depth of oil saturation in the ice and the depth of the oil pools.

The quantification of these classifications included the variables of the depth of oil penetration into the ice and the percent oil concentration by volume for the penetration depth. Actual percent composition by volume was determined by melting selected samples from areas representing each major type of oiling. Irregularities in the shape of the ice within rubble fields required that the initial surface area estimates as derived from aerial photographs be doubled. Weathered losses from each type of oil/ice involvement were estimated on the basis of samples taken from representative areas which were analyzed for percent loss of their volatile portions. The percent loss for each of the six categories of oil concentrations was then averaged and factored into the volumes present. It should be noted that the analysis is based on the best available field information and that the results are an approximation. There are certain limitations to these estimates, including an inability to account for the initial losses in the water column prior to the stabilization of oil within the ice, an inability to quantify the amount of oil hidden beneath the rafted floes, the arbitrary classification of the oil concentrations, and the approximation of the amount of oil loss due to weathering.

The results of the oil mass balance analysis are presented in Table 2. The first column lists the six oil/ice categories from previously described observations and the burn site. The following column provides the areal coverages. The third column provides the mean percent of oil saturation,

and the fourth column gives the depth of oil saturation. Column five shows the approximate volumes of oil associated with each category. The last column lists the volumes of weathered oil based on percent loss of volatiles.

It is interesting to note that less than 30% of the total oil spilled was detectable in the form of large concentrated pools. Also, 15% of the oil was in shallow pools, making approximately 45% of the oil available in a form capable of being pumped. However, the logistical problems of getting to these widely scattered patches of oil before the snow fell prevented the cleanup crews from taking full advantage of this natural containment. The majority of the 81,150 gallons spilled was spread over an area of approximately 95,000 m^2, with an average concentration of one gallon per 1.2 m^2. This oil was primarily in the form of contaminated ice which could not be practically recovered.

APPLICATION OF THE BUZZARDS BAY OBSERVATIONS TO HIGHER LATITUDES

There are several important environmental differences between the waters of Buzzards Bay and those of the more northern ice covered coasts. First, the ice growth season in the Bay during the winter of 1977 was relatively short, lasting approximately two months, from January 1 to February 22. Second, by Arctic standards, the ice in the Bay was thin, on the order of 0.3 m, even though rafting and ridging in the center of the channel increased the thickness to at least 1 m. Third, the ice was nearly desalinated, or practically fresh, making the ice much less porous than Arctic sea ice. Fourth, the most important difference is the unusual geometry of Buzzards Bay. It is an enclosed bay, with Cape Cod Canal extending from the northern end of the bay through the Cape Cod Peninsula to Cape Cod Bay. Due to the three hour time difference in the phase of the tides between Buzzards Bay and Cape Cod Bay, there is a strong flow of water in and out of the canal, with velocities as high as 2.3 ms^{-1} in the canal, and 0.5 ms^{-1} at the end of Stony Point Dike (Wilcox 1958).

In addition to these environmental conditions that may not exist in other cold region aquatic environments, the properties of the spilled oil are important. The No. 2 home-heating oil spilled in the ice covered waters of Buzzards Bay had a high volatility and low specific gravity, viscosity, and surface tension as compared to crude oil. Also, these properties were not very temperature dependent. Therefore, the oil flowed easily, was thinly spread, and penetrated into the snow and ice. Crude oil properties are normally very temperature dependent and the surface tension, specific gravity, and particularly the viscosity increase significantly with decreasing temperature. This would mean that crude oil would not flow as easily into cracks, would not spread as easily, and would tend to adhere to, rather than penetrate into, the snow and ice.

To make a statement that all spills occurring in the active ice zone or shear zone will be similar to the Buzzards Bay spill would be inaccurate. However, for No. 2 oil spilled underneath the ice where rafted ice, hummocks, pressure ridges, and leads have formed, the oil most probably will find its way to the surface if the relative velocity between the ice and the sea water

exceeds the threshold velocity necessary to transport the oil and the temperature is not low enough to freeze the oil into the ice. The oil pooling on rafted ice may prove very useful when cleanup attempts are made. Oil transport by oily ice floes will also extend the range of an Arctic spill. Further research is required to help understand the many types of oil, ice, and snow interactions possible in higher latitudes and the eventual fate of these spills.

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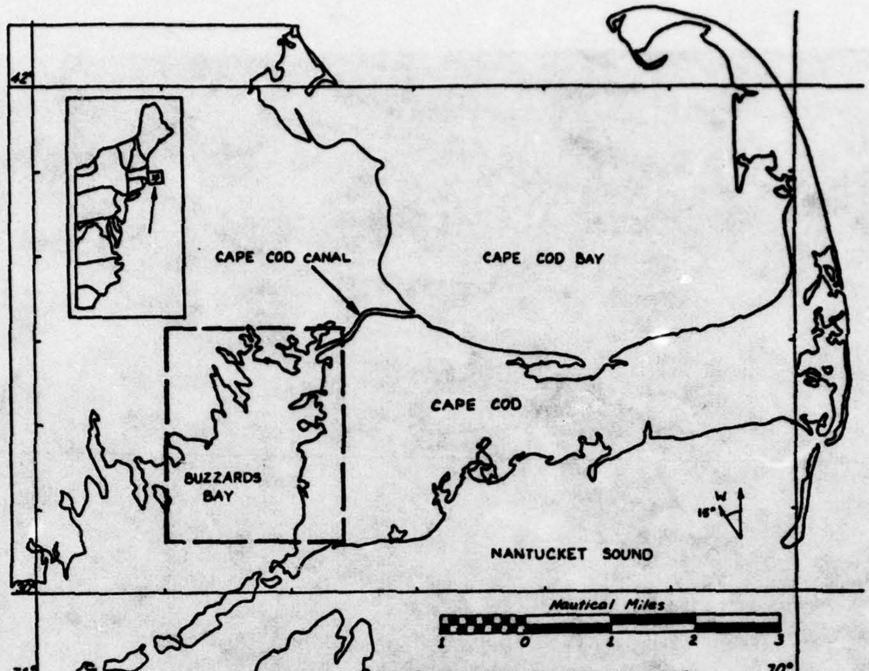

Figure 1. COAST OF MASSACHUSETTS.

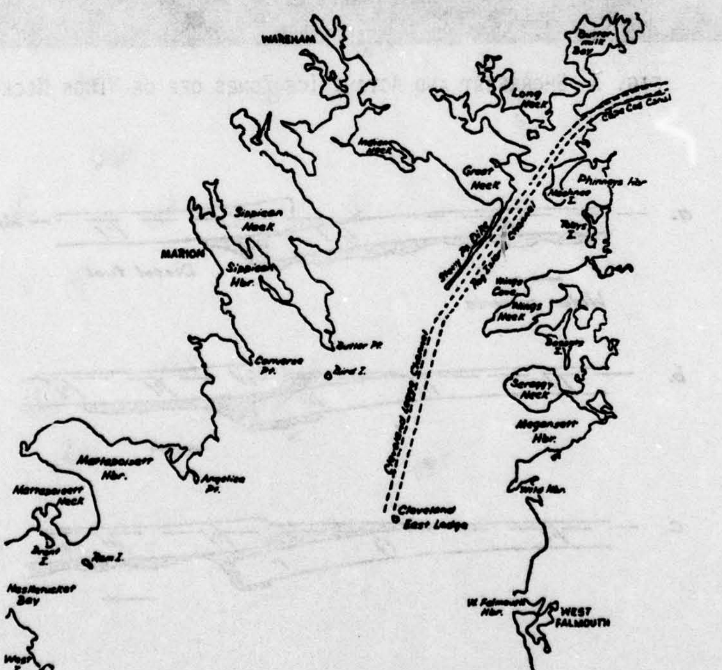

Figure 2. NORTHERN BUZZARDS BAY

FIG. 3 SHOREFAST AND ACTIVE ICE ZONES OFF OF WINGS NECK

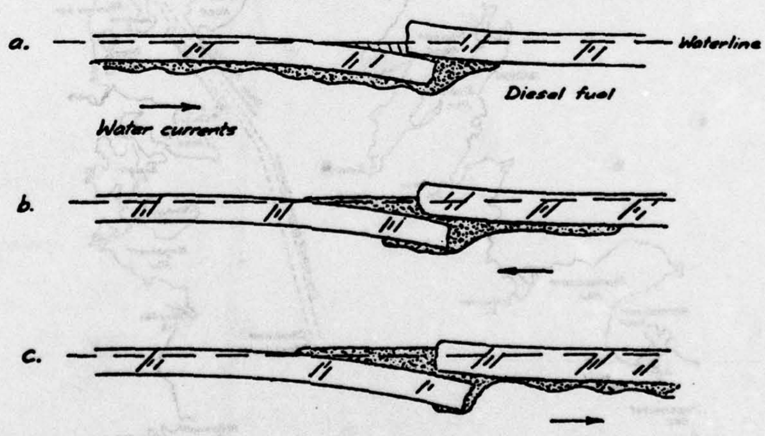

FIGURE 4 FLOW OF OIL IN RAFTED ICE a) OIL FLOWING UNDERNEATH THE ICE COMES IN CONTACT WITH RAFTED ICE. b) CURRENT REVERSAL ENCOURAGES OIL FILLING INTO RAFTED ICE POCKET c) REVERSAL OF CURRENT SWEEPS UNSHELTERED OIL AWAY

FIG. 5 LARGE OIL POOL FROM RAFTED ICE FORMATION

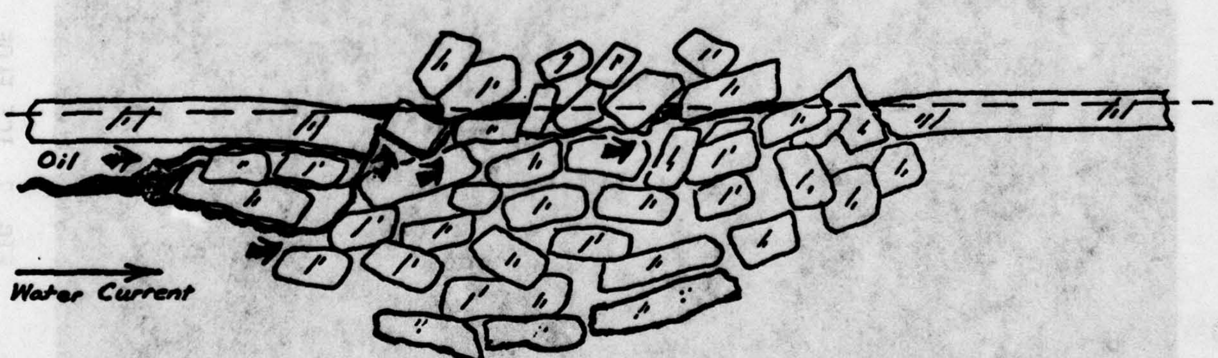

FIGURE 6 OIL FLOWING INTO AN IDEALIZED CROSS SECTION OF A HUMMOCK

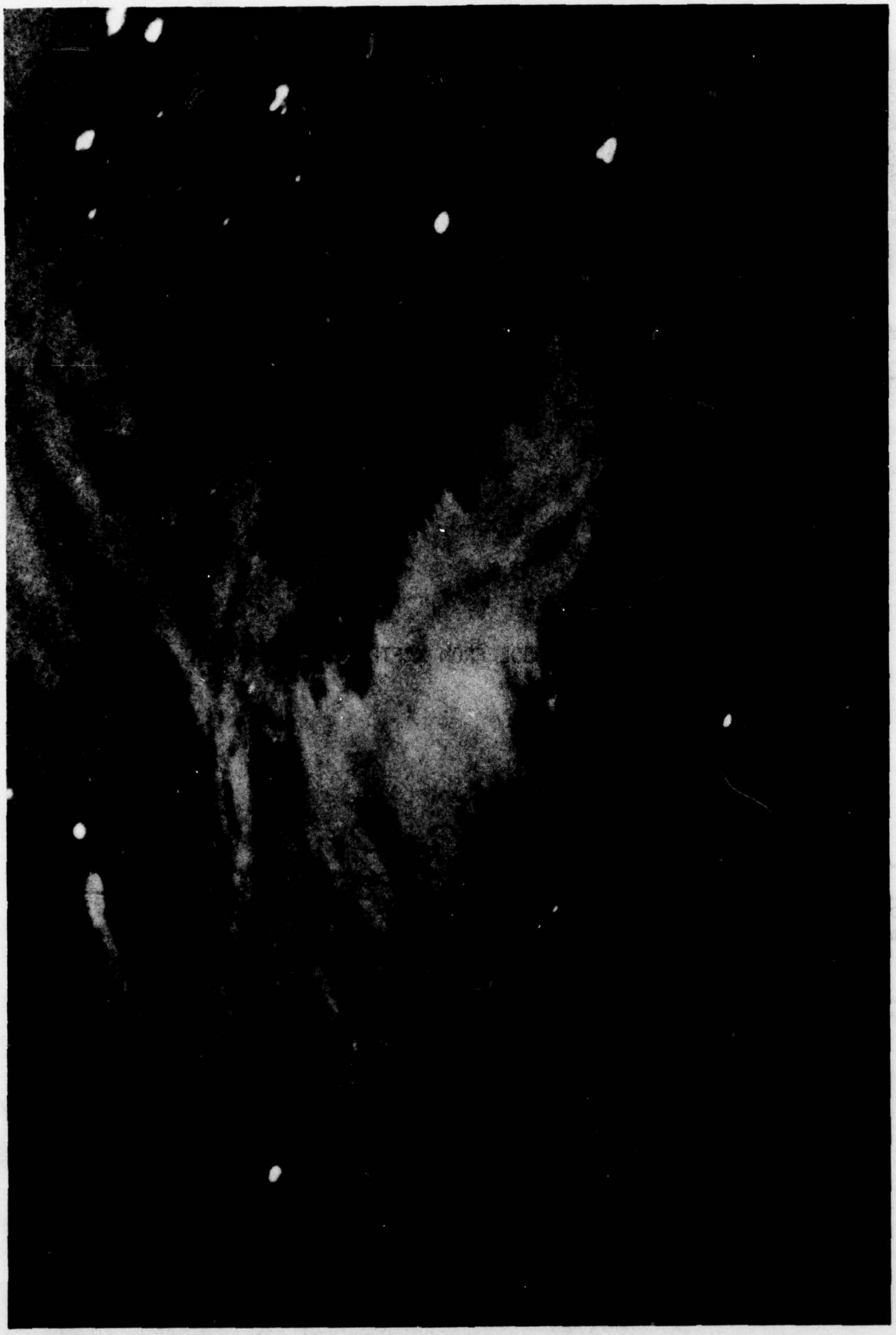

FIG. 7 ICE FLOE, 5 M DIAMETER, BLEEDING OIL SHEEN AS IT MELTS ON FEBRUARY 12

TABLE 1 WEATHERED OIL SAMPLES TAKEN FROM DIFFERENT FIELD CONDITIONS ON FEBRUARY 10

Location	Field Condition	Percent Loss Alkanes	Approximate Percent Loss Arenes	Approximate Total Percent Loss
Wings Neck Tower	Oil underneath ice near edge of rafted ice. Oil was approx. 13 mm thick	4%	14%	6%
Wings Neck Tower	Oil in ice sheltered by overlying ice sheet	4%	16%	6%
Wings Neck Cove	Oil in ice near edge of ice floe. Sample taken from top 38 mm of ice core of medium stained ice	5%	20%	8%
Wings Neck Cove	Slush oil/snow mixutre from shallow oil pool in hummock	7%	31%	12%
Wings Neck Cove	Oil taken from deep oil pool in rafted ice	7%	38%	13%
Wings Neck Cove	Heavily oiled stained ice from ice floe near edge of small oil pool	10%	33%	15%
Wings Neck Tower	Ice piece 0.3 mm thick taken from small pressure ridge. Ice appeared to be medium stained	9%	38%	15%
Wings Neck Tower	Wind blown oil on top of ice	21%	54%	28%
Wings Neck Tower	Wind blown oil on top of ice	25%	64%	33%
Wings Neck Cove	Ice piece rotated in the air. Scraped off top of medium stained oily ice	29%	58%	35%
Wings Neck Cove	Ice piece rotated in air. Scraped off top of lightly stained oily ice	37%	89%	47%

TABLE 2 OIL BUDGET FOR BOUCHARD #65 OIL SPILL, JANUARY 1977

Type of Oil/Ice Configuration	Total Area (m^2)	% Oil Saturation	Depth of Saturation (m)	Volume (gallons)	Weathered Losses (gallons)
Deep Oil Pools	700	100.0	0.13	24,000	3,100
Shallow Oil Pools	1,800	100.0	0.025	12,000	1,400
Heavily Stained Ice	9,800	5.0	0.05	13,000	2,000
Medium Stained Ice	29,700	1.0	0.05	8,000	1,500
Lightly Stained Ice	32,500	0.5	0.05	4,000	1,900
Windblown Oil	14,700	50.0	0.003	6,000	1,800
Burn Site (heavily stained ice and shallow oil pools)	5,600	5.0	0.05	4,000	500
TOTALS	≈94,800			≈71,000	≈12,000

WEATHERING ESTIMATIONS FOR SPILLED OIL FROM BOUCHARD NO. 65

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ABSTRACT

Eleven ice and snow samples collected in the vicinity of the No. 2 fuel oil spill from the barge Bouchard No. 65 (Buzzards Bay, Massachusetts, 1977) were analyzed for saturated and aromatic hydrocarbons by high resolution gas chromatography. Similar analysis of samples from the Bouchard No. 65 cargo indicated that the aromatic hydrocarbon level was somewhat less than that of the No. 2 fuel oil spilled from the barge Florida in 1969. Weathering of alkanes and arenes was estimated by comparing quantitative changes in these hydrocarbons relative to the cargo oil. The arenes exhibited greater percent losses than the alkanes. Losses generally correlated with exposure of samples to the atmosphere. Overall oil losses were estimated by taking a weighted average of the alkane and arene loss estimates.

INTRODUCTION

When the barge Frederick E. Bouchard No. 65 ran aground in the icy waters of Buzzards Bay, Massachusetts in January 1977, an estimated 81,000 gallons of No. 2 fuel oil spilled into the marine environment (Baxter et al. 1978). This area of Cape Cod has a prior record of No. 2 fuel oil spills, including three within the past decade. The most serious of these, from the barge Florida in 1969, resulted in extensive immediate damage to important local marine biota (Hampson and Sanders 1969, Blumer et al. 1971, Sanders et al. 1972), with long range effects (Michael et al. 1975, Stegeman and Sabo 1976) extending to the present day (Baxter et al. 1978). In view of these previous incidents, there was concern for the environmental fate and effects of this latest oil spill. To assess changes due to weathering, oil-impregnated samples of ice, snow, and water were collected by ARCTEC, Inc. from the Buzzards Bay area thirteen days after the Bouchard No. 65 spill, and forwarded with reference cargo samples to our laboratory for hydrocarbon analyses. High resolution gas chromatography (GC) was employed to investigate compositional changes in the recovered spilled oil samples with respect to the cargo reference oil.

METHODS

Thirteen samples of ice cores, snow, and water collected from the vicinity of the Bouchard No. 65 spill for the National Oceanic and Atmospheric Administration (NOAA) were shipped frozen to the NOAA National Analytical Facility. Upon thawing, 11 of the environmental samples (Table 1) contained sufficient oil for analysis. Aliquots of oil from these samples and the barge were separated by silica gel chromatography into two fractions containing primarily (a) saturated aliphatic hydrocarbons and (b) aromatic hydrocarbons, respectively. These fractions were analyzed according to published procedures (MacLeod *et al*. 1977).

GC peak areas were recorded for the *n*-alkanes, C_9-C_{22}, plus pristane and phytane in the aliphatic fraction and for 21 arenes (Table 2) among the aromatics. For direct graphical comparisons, the peak areas of the 16 alkanes in each sample were converted to a common scale by normalizing relative to the *n*-$C_{17}H_{36}$ peak area. The resulting normalized peak areas were then plotted in bar-graph form for visual comparison between the samples and the reference. The normalized peak areas were also used to determine percent losses among the 16 alkanes according to equation 1:

$$\text{percent loss} = \frac{R - S_x}{R} \cdot 100 \qquad (1)$$

where R = the sum of the normalized peak areas for the 16 reference alkanes and S_x = the analogous sum for a particular sample, x. For graphical comparison of the 21 arenes among the samples, the peak areas of these arenes in a sample were likewise converted to a common scale by normalizing relative to the phenanthrene peak area in the sample. Analogous substitution of arenes for alkanes in equation 1 gave the percent loss of the 21 arenes in each sample. Overall estimates of the percent loss in the spilled oil samples were calculated according to equation 2:

$$\begin{array}{l}\text{percent loss}\\ \text{of total oil}\end{array} = (1-y)(\%\ \text{alkane loss}) + y(\%\ \text{arene loss}) \qquad (2)$$

where y = decimal fraction of aromatic hydrocarbons in the cargo oil.

RESULTS AND DISCUSSION

To begin with, it should be emphasized that this study involved a limited number of samples collected in a limited geographical area on February 10, 1977, 13 days after spillage of a known No. 2 fuel oil under icy inland marine environmental conditions (Baxter *et al*. 1978). Since this Bouchard spill occurred in the same general area (Buzzards Bay) as the earlier disastrous No. 2 fuel oil spill from the barge Florida, there was concern that the consequences of this Bouchard spill would be comparable. Baxter *et al*. (1978) indicate that this was not the case. Apparently, the main features common to both spills were that they involved No. 2 fuel oils spilled from barges in the Buzzards Bay area. Hence, we wish to stress that the results of this study pertain

to the unique set of circumstances surrounding this Bouchard spill; facile extrapolation to other spill circumstances should be avoided.

It is well known that oils spilled in the marine environment are subject to a number of physical, chemical, and biological processes known collectively as "weathering" (Clark and MacLeod 1977). These weathering processes can alter the original hydrocarbon composition of a spilled oil, eventually beyond recognition. However, the extremely frigid conditions during the 13 days between spillage and sampling suggested that weathering of the spilled Bouchard No. 2 fuel oil probably was confined to evaporation and dissolution; probably little biodegradation or photochemical oxidation occurred.

High resolution gas chromatography separated the Bouchard No. 65 cargo oil into hydrocarbon components shown in Figure 1. No significant variation in this compositional profile was observed among reference oil samples from cargo ports 3, 5 or 6 of the barge. Likewise, gas chromatograms of oil found under the ice 13 days after the spill (Table 1, samples 1 and 2) were virtually identical to Figure 1. In contrast, spilled oil more exposed to the air (Table 1, sample 10) had a GC profile (Fig. 2) which showed losses in the more volatile components (peaks 9-13). Despite evidence of weathering, Figure 2 is sufficiently similar to Figure 1 (especially from peak 12 onward) as to leave little doubt that the oil originated from the Bouchard No. 65 barge. This was true for all the environmental samples in Table 1.

As shown in Figure 1, the n-alkanes (numbered peaks) are the major components of the Bouchard cargo. Most of this cargo oil consisted of aliphatic (67%) and aromatic (33%) hydrocarbons according to GC analysis. The aromatic hydrocarbon content of the Bouchard cargo is somewhat less than that of the Florida cargo which was determined to be 41% by similar methods (Blumer et al. 1970).

The prominence of the n-alkanes in the cargo oil (Fig. 1) made them useful marker compounds in the identification of changes in the oil; not only were they distributed at regular intervals throughout the GC profile, but their mass distribution also appeared to parallel that of the cargo oil. Hence, comparative changes in 14 n-alkanes (C_9-C_{22}) and 2 branched alkanes (pristane and phytane) were used to estimate weathering effects on the aliphatic hydrocarbon fraction. To compare changes in the recovered spilled oil with respect to the presumed original composition, the GC peak areas of these 16 alkanes were converted to a common relative scale by normalizing with respect to the peak area of an alkane (e.g., n-$C_{17}H_{36}$) which showed no comparative weathering loss. Generation of normalized peak areas for the selected alkanes in each sample permitted direct graphical comparison of the alkane composition in the environmental samples relative to that of the cargo oil. Graphical comparison of the n-alkanes in the cargo and samples 5 and 11 (Table 1) is shown in Figure 3. Note that loss of compounds occurred in the C_9 to C_{15} range and that little weathering is evident in these samples above n-$C_{15}H_{32}$.

Although the aromatic hydrocarbons constituted the lesser portion of the cargo oil, information about their losses is needed to evaluate changes in oil from weathering. Unlike the n-alkanes, the major arenes were not evenly spaced throughout the GC profile (compare Figs. 1 and 4). Table 2 lists the 21 arenes selected to represent the aromatic fraction. Phenanthrene, one of the few candidates not to show comparative weathering changes in the samples, was used as the normalizing arene. Figure 5 shows the graphical comparison of normalized arene peak areas from the same samples whose alkanes were compared in Figure 3. Some loss occurred in the 15 compounds depicted, with the greatest losses occurring in sample 11. Examination of sample 11 shows that the benzene homologous series had virtually disappeared and that definite losses occurred in naphthalene, 1-methylnaphthalene (1MN) and 2-methylnaphthalene (2MN). These results confirm that the evaporative process in weathering is related to molecular weight and chemical structure.

Weathering losses in the recovered spilled oils vs. the reference cargo oil were compared numerically by calculating the percent losses among the selected alkanes and arenes according to equation 1. Results are shown in Table 1. In every environmental sample in Table 1, percent losses were greater among the arenes than among the alkanes. This may be due to the greater volatility and water solubility of the selected arenes than of the selected alkanes. The percent losses of these alkanes and arenes (Table 1) were subjected to regression analysis and found to have an approximate linear relationship. Under the limited weathering regime postulated for this spill, this empirical relationship could be used to estimate arene percent loss, if only the percent loss of alkanes were determined by direct GC analysis of the neat oil (without fractionation by adsorption chromatography).

The observed percent loss differences between the alkanes and arenes for each environmental sample in Table 1 demonstrate that spilled No. 2 fuel oil was definitely altered in composition, even under the frigid conditions of this spill. Thus, although all these recovered spilled oil samples retained similarities in their GC profiles that unquestionably relate them to the original Bouchard No. 65 cargo, a recovered oil (e.g., Table 1, sample 11) may have lost as much as 9/10 of its aromatic hydrocarbons while retaining 1/2 of its total mass. Mass measurement of "oil" found in environmental samples is therefore insufficient to estimate its toxicity to marine life. Hence, estimates of percent loss of "total oil" in Table 1 may be useful in mass balance calculations but should not be employed alone when considering toxic impact.

SUMMARY

Analysis of the No. 2 fuel oil cargo of the Bouchard No. 65 barge indicated that it contained a lower concentration of the aromatic hydrocarbons in the No. 2 fuel spilled from the barge Florida in 1969. Oil from 11 environmental samples collected after the Bouchard spill was shown to have originated from the Bouchard cargo. Alkane losses due to weathering occurred in the C_9-C_{15} range. The more toxic aromatic

components tended to dissipate more rapidly than the rest of the oil. In one sample, as much as 89% of the measured arenes were lost, even under the frigid conditions of the spill. The percent loss estimates generally correlated with exposure of the oil to conditions that could increase evaporative weathering.

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Table 1. Weathering estimates for recovered oil samples collected in the Wings Neck area of Buzzards Bay on February 10, 1977 (13 days after the Bouchard No. 65 spill).

Sample No.	Field Condition[a]	Approximate Percent Loss: Selected Alkanes	Selected Arenes	Total Oil
1.	Oil underneath ice near edge of rafted ice. Oil was approx. 1.3 cm thick	4%	14%	7%
2.	Oil in ice sheltered by overlying ice sheet	4%	16%	7%
3.	Oil in ice near edge of ice floe. Sample taken from top 38 mm of ice core. Medium stained ice	5%	20%	10%
4.	Slush oil/snow mixture from shallow oil pool in hummock	7%	31%	15%
5.	Oil taken from rafted oil pool	7%	38%	17%
6.	Heavily oil stained ice from ice floe near edge of small oil pool	10%	33%	18%
7.	Ice piece 0.3 mm thick taken from small pressure ridge. Ice appeared to be medium stained	9%	38%	19%
8.	Wind blown oil on top of ice	21%	54%	32%
9.	Wind blown oil on top of ice	25%	64%	38%
10.	Ice piece rotated in air. Scraped off top of medium stained oily ice	29%	58%	39%
11.	Ice piece rotated in air. Scraped off top of lightly stained oily ice	37%	89%	55%

[a]From field notes of Paul Delauriers, ARCTEC, Inc. (Baxter *et al.*, 1978)

Table 2. Arenes quantitated by GC analysis.

Symbol	Name	Symbol	Name
TOL	toluene	2MN	2-methylnaphthalene
ETB	ethylbenzene	1MN	1-methylnaphthalene
MPX	m,p-xylene	BPH	biphenyl
OXY	o-xylene	C_2N	a C_2 naphthalene
IPB	i-propylbenzene	TMN	a trimethylnaphthalene
NPB	n-propylbenzene	DBT	dibenzothiophene
MEB	a methylethylbenzene	PHN	phenanthrene
TMB	a trimethylbenzene	MDT	a methyldibenzothiophene
IND	indan	MDT	a methyldibenzothiophene
C_4B	a C_4 benzene	C_2P	a C_2 phenanthrene
NPH	naphthalene		

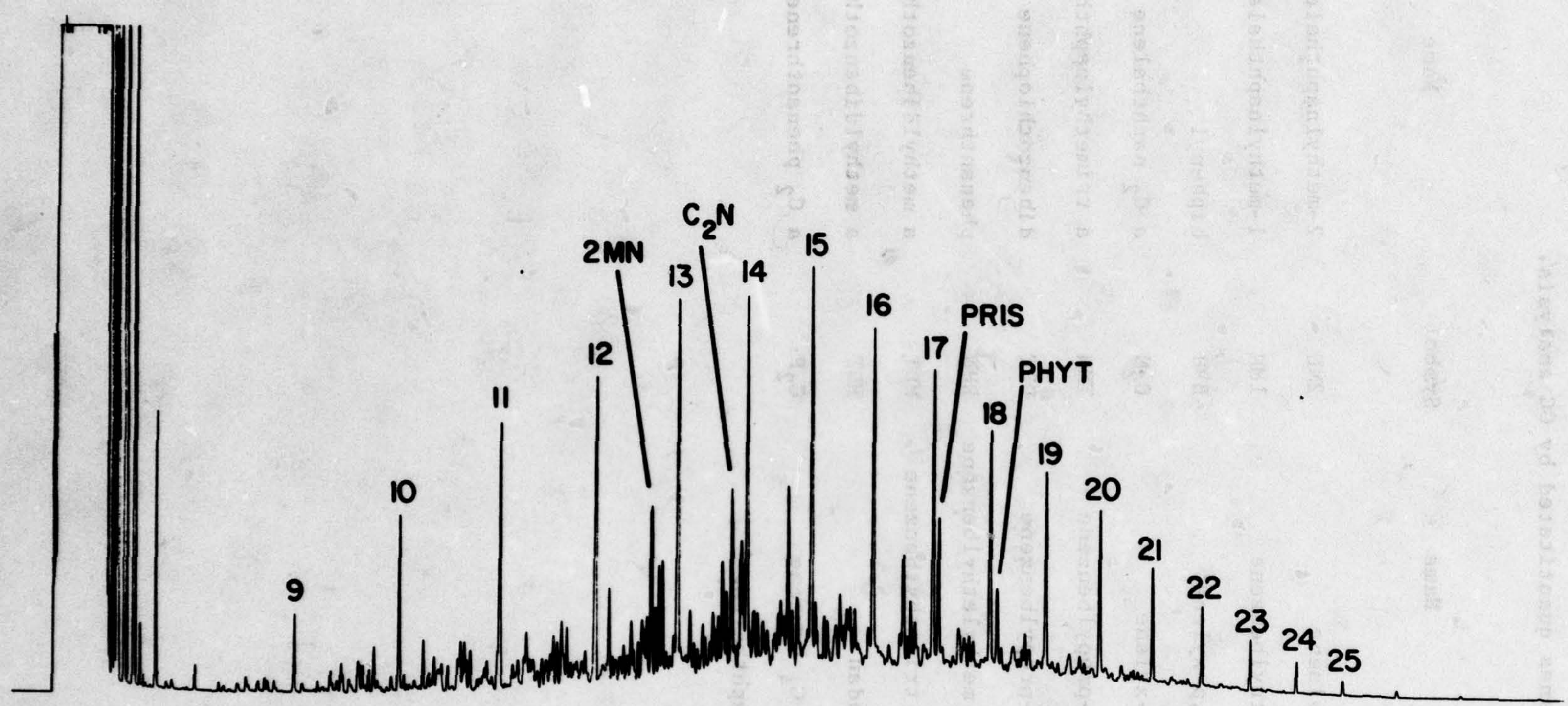

Figure 1. High resolution gas chromatogram of <u>Bouchard No. 65</u> cargo. Numbers denote <u>n</u>-alkane chain length. PRIS = Pristane; PHYT = Phytane; 2 MN = 2-Methylnaphthalene; C_2N = a dimethylnaphthalene. 20 m x 0.25 mm WCOT glass column coated with SE-30. 2 ul splitless injection, vaporization at 280°C, split (10:1) after 12 sec with 14 psi helium carrier gas. Column temperature 40°C for 5 min, then programmed to 270°C at 4°/min.

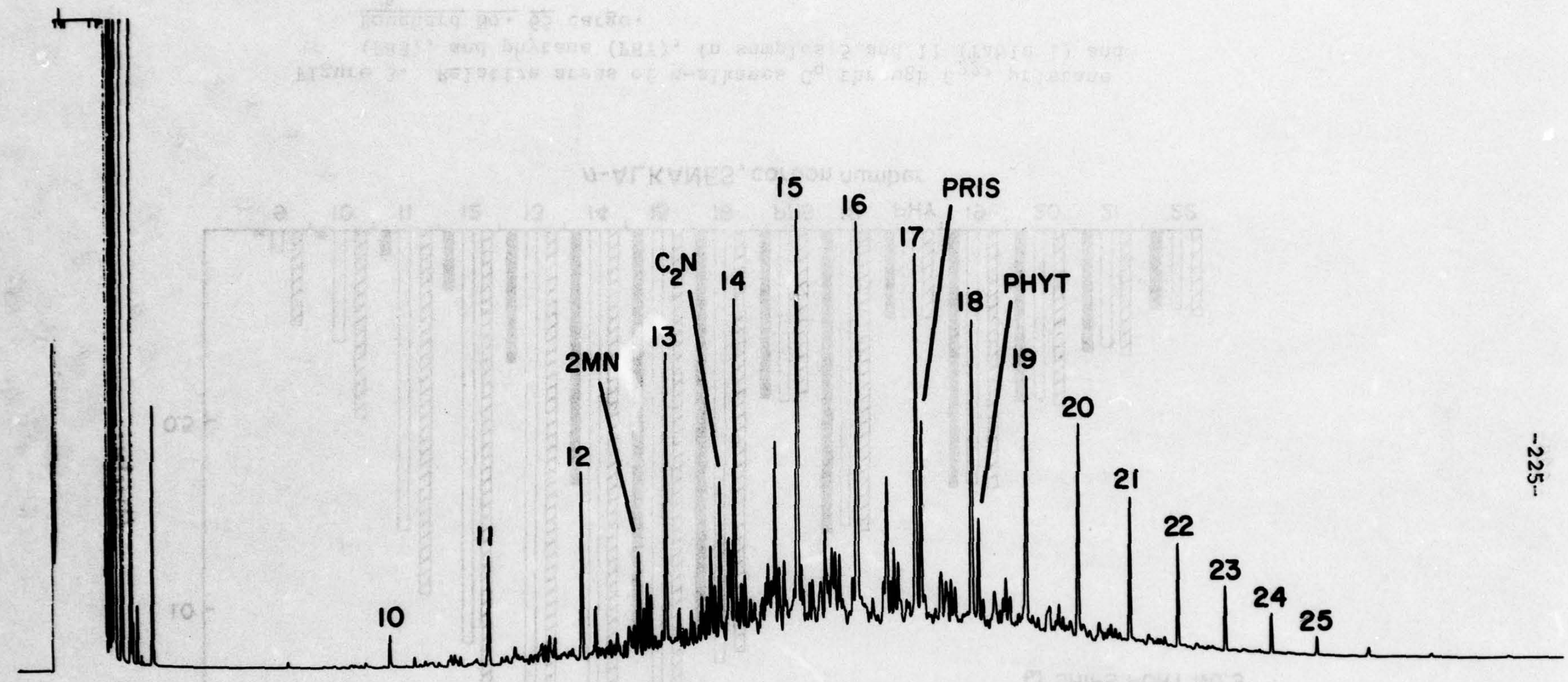

Figure 2. High resolution gas chromatogram of hydrocarbons in sample 10, Table 1. Conditions and peak identities same as for Figure 1.

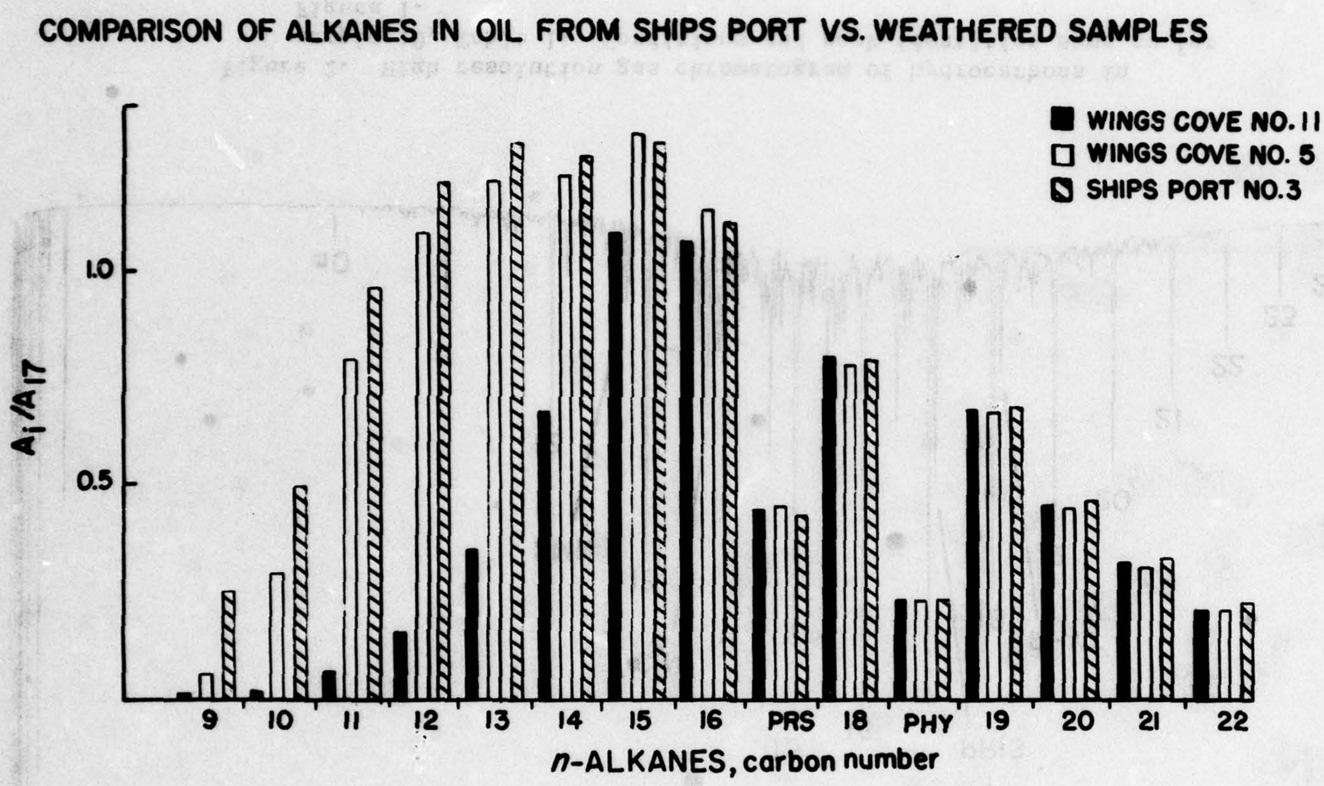

Figure 3. Relative areas of n-alkanes C_9 through C_{22}, pristane (PRS), and phytane (PHY), in samples 5 and 11 (Table 1) and Bouchard No. 65 cargo.

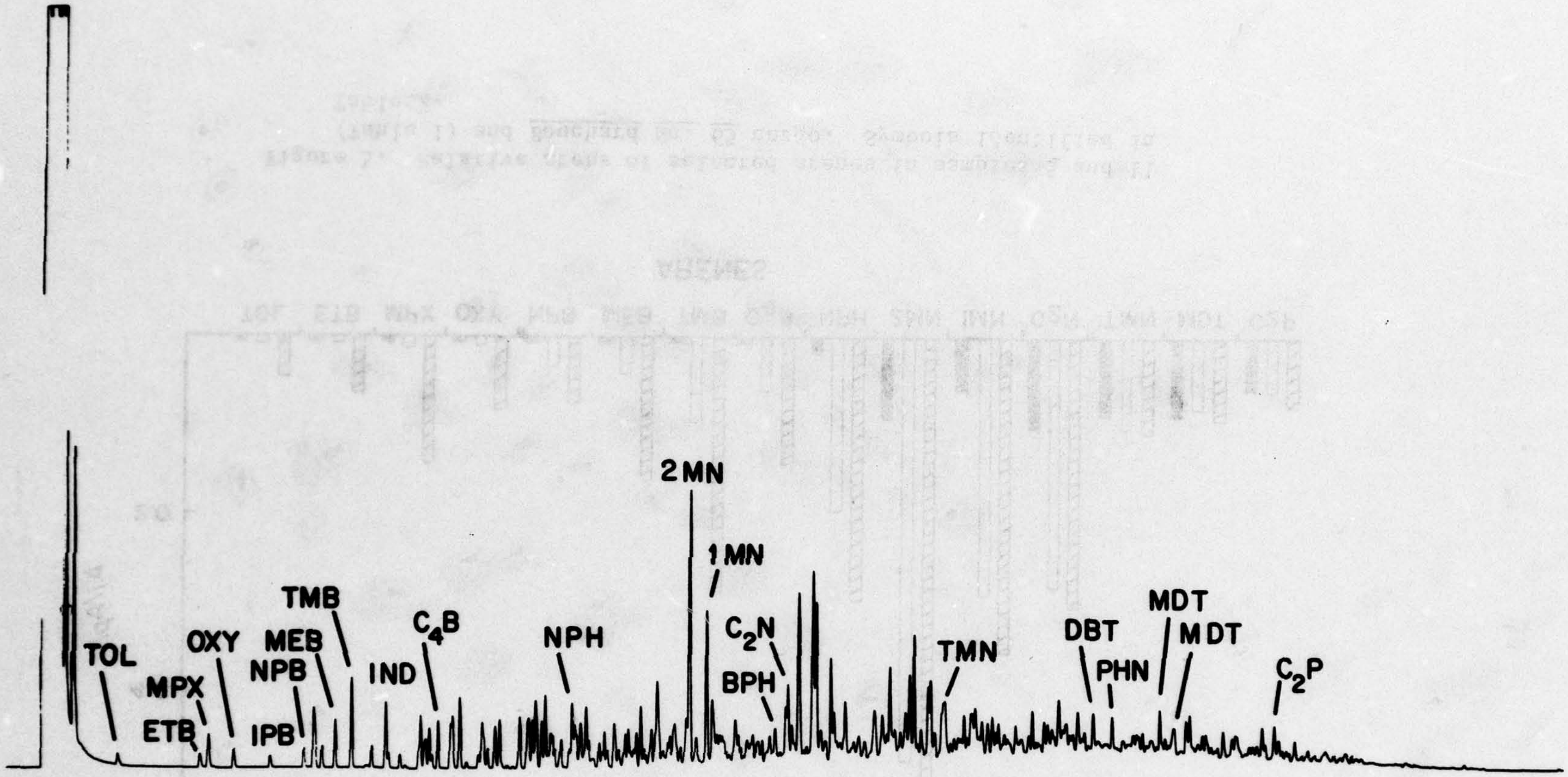

Figure 4. High resolution gas chromatogram of aromatic hydrocarbons from Bouchard No. 65 cargo. Conditions same as for Figure 1 except column coated with SE-54. Symbols identified in Table 2.

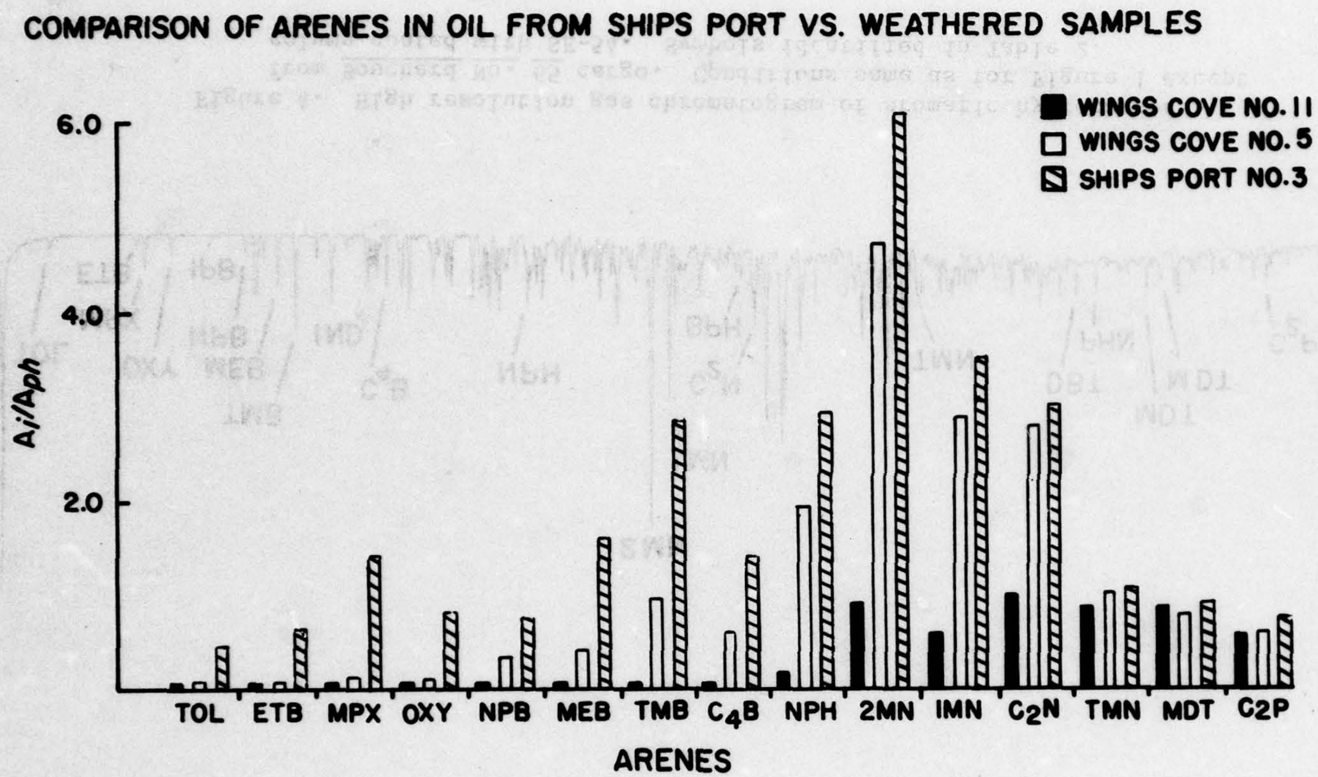

Figure 5. Relative areas of selected arenes in samples 5 and 11 (Table 1) and Bouchard No. 65 cargo. Symbols identified in Table 2.

<u>THE IMPACT OF THE NEPCO #140 BARGE SPILL IN THE ST. LAWRENCE RIVER (6/23/76)</u>

Chairman: ROYAL NADEAU
U.S. Environmental Protection Agency

THE ROLE OF RESOURCE MANAGEMENT BIOLOGISTS AT OIL SPILLS

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United States Environmental Protection Agency
Region II
Edison, New Jersey

and

John R. Hanlon
United States Fish & Wildlife Service
Cortland, New York

THE ROLE OF RESOURCE MANAGEMENT BIOLOGISTS AT OIL SPILLS

by

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Classically, at the time of an oil spill, the Environmental Protection Agency and U.S. Fish & Wildlife Service as primary members of the Regional Response Team serve as the environmental watch and advisors to the On-Scene Coordinator (OSC) on environmental matters. The EPA's role on the Resonse Team is to identify environmentally sensitive areas and provide information to the OSC as to the mitigative measures that can be used to protect these sensitive areas or lessen the impact of the oil and the clean-up operation. EPA, by legislative mandate, is concerned for the water quality particularly as it relates to biological resources. Impact from an oil spill can result in:

- Direct impact to the aquatic populations
- Secondary impact ie. contamination of food webs by persistent petroleum compounds

In this respect, EPA is expected to be able to provide technical information in regards to toxicity and bioaccumulation potential of various compounds present in the spilled oil.

The U.S. Fish & Wildlife Service has jurisdiction over migratory waterfowl and protection of endangered species and as a primary member of the Response Team is concerned with protecting these species for oil contamination. By mandate, the U.S. Fish & Wildlife Service agents work closely with state fish and game officials to accomplish these resource management goals. The U.S.

Fish & Wildlife Service is concerned with restoring those populations and areas already affected or otherwise contaminated by the oil spill.

To perform these functions effectively, means that environmental information and/or data from a variety of sources must be assembled, assimiliated and interpreted for the OSC.

Initially, the OSC will request information on the biological communities and populations being affected by the spilled oil. The OSC will be most concerned for any waterfowl populations and habitats that may have become oiled. Secondly, the OSC will want to know about ecologically sensitive areas which are apt to become oiled as time progresses. This information is important for making critical decisions relative to deployment of equipment and manpower in order to protect these areas from becoming oiled.

For the biological communities already impacted, there is a strong need to characterize the initial impact ie. acute toxic responses of various affected populations. It is in the area of biological impact analysis that resource management agencies can be of great service by providing technical data and interpretation of these data to the OSC and the Response Team.

To optimize gathering meaningful and accurate information and to fulfill each agency's respective role, segregation of activities is often necessary. This means that aquatic biologists may be performing a different role from fisheries or wildlife biologists. It is important to stress that a segregation of activities is necessary to optimize available manpower and resources. To insure efficient utilization of these resources, a plan of action or "game plan" must be formulated and implemented. Much of this should be spelled out in Contingency Plans however some modifications will inevitably be necessary at the spill scene. There has to be enough flexibility to allow modification in the field to accomodate the unique conditions of each spill.

The NEPCO 140 spill provided the opportunity for biologists from federal and state resource management agencies to perform in concert and still be mindful of their respective agencies' role on the Response Team. Working together, these biologists provided the OSC with crucial information that was utilized for identifying problems or sensitive areas and establishing priorities for clean-up efforts.

A model spill would involve a variety of activities that biologists would perform (Nadeau, 1977). The NEPCO 140 spill serves as a good example as it approached the ideal situation in terms of cooperation, available resources and responsiveness. The spill

scenario for a model spill would probably be as follows:

PREFIELD ACTIVITY

- Upon arriving on scene, contact the OSC to obtain a briefing on the spill. Obtain maps of the affected areas and a field radio unit that is on the same frequency as the base radio in the command post.
- Become informed of known or suspected damaged or threatened areas. In the case of the NEPCO 140 spill, there were several freshwater marsh areas plus a Great Blue Heron rookery affected by the spill. The New York State Department of Environmental Conservation biologists provided the most up-to-date and detailed information to the EPA and Fish & Wildlife representatives on the marsh areas and bird rookery.

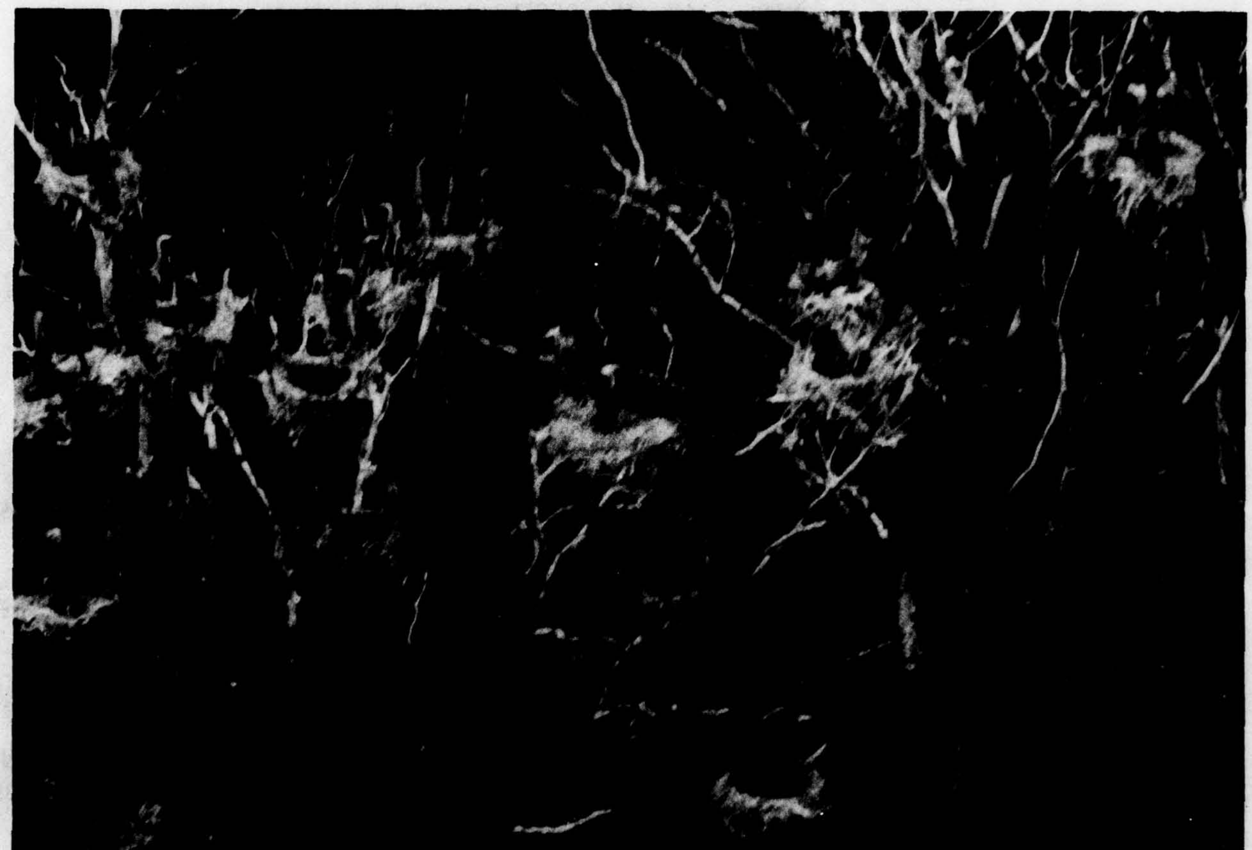

Figure 1. Great Blue Heron Nests with Fledglings on Ironsides Island

- Decide upon the information and observations which will be most helpful to the OSC and Response Team. At this point, contingencies for handling and cleaning oiled birds should be discussed and implemented. In the case of the NEPCO 140, this involved ordering twenty barrels of solvent, large (30" diameter) balloons of various colors, rolls of 50 lb. test monofilament fishing line. Simultaneously, the DEC Fish & Game personnel selected and prepared a site for a bird cleaning operation. This involved obtaining pens, washtubs, hair dryers, gloves and other materials.

- Formulate a plan of action whereby various biological communities are delineated for sampling. This selection should be on the basis of areas already or likely to be affected in combination with knowledge of the fate and behavior of the types of oil spilled. In the case of the NEPCO 140, the DEC biologists were able to access the marshes using canoes and four wheel drive vehicles. It was decided that the affected marshes

Figure 2. Oiled Marshes in Chippewa Bay, Thousand Island Region in St. Lawrence R.

should be examined to determine the immediate impact to game and non-game populations. This task was divided amongst all three agencies. In addition, the EPA and U.S. Fish & Wildlife biologists sampled oiled and unoiled periphyton communities plus obtaining a sample of the weathered oil for toxicity testing.

Before we left the command post, we briefed the OSC and Response Team on our activities, purpose and the places we would all be located. We also indicated the approximate time we were to rendezvous back at the Command Post.

FIELD ACTIVITIES

It is most important for damage assessment to:

- Locate and sample affected areas and to find similiar but unaffected areas for control sites.

- Collect living specimens in large containers for toxicity testing. These tests are most important for gaining insight on possible latent toxicity. For these tests, spilled oil is added to a number of the containers while others are left to serve as controls.

  For the NEPCO 140 spill, a bioassay of this nature was set up using some of the organisms collected in the periphyton. These included amphipods, isopods, aquatic insect larvae, fish eggs and fry.

- Particularly for damage assessment surveys, assume that all the data collected will eventually be used in legal proceedings. Consequently, the following should be adhered to:

  - Proper sampling methodology, accurate label-ling and preservation techniques must be used.

  - Comprehensive photographic documentation with prints, labelled to provide vivid illustration of conditions present.

  - Maintain a complete chain of custody for all samples collected and analyzed.

The spill scene requires different approaches and a special criteria for assessing environmental damage within a concentrated time frame. Therefore, we tend to look for overt responses like:

- Overt damage to the fisheries and wildlife populations and habitats.
- Results of the latent toxicity tests. In most cases this information will not be available for 24-48 hours after initiation.
- Potential for additional sensitive habitats to become oiled.

With the above information and ancillary field observations, the biologists can collectively provide the OSC and Response Team with:

- Recommendations on those biological communities and habitats that should receive priority or special consideration during the clean-up operation.

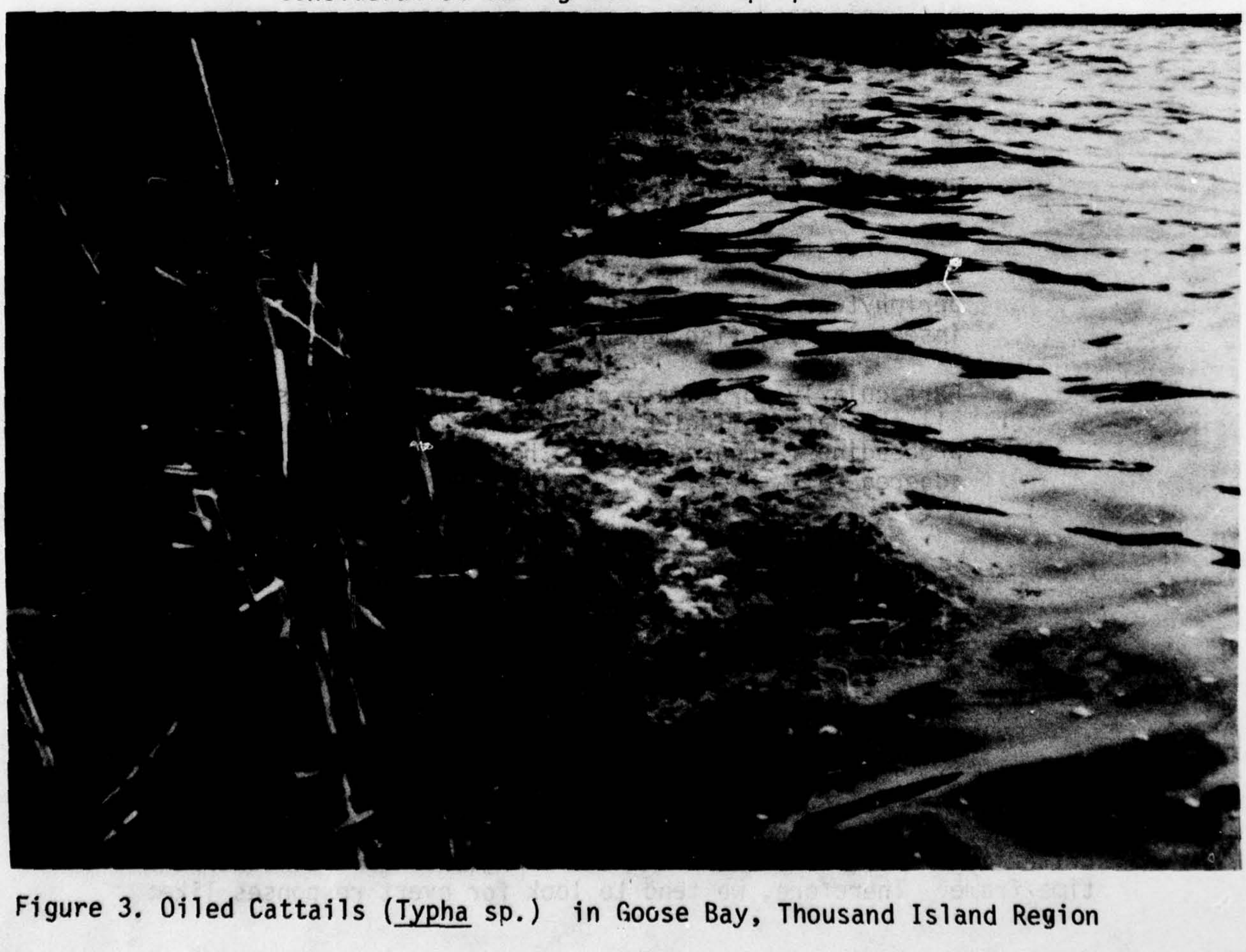

Figure 3. Oiled Cattails (Typha sp.) in Goose Bay, Thousand Island Region

In the case of the NEPCO 140, the biologists recommended that diversion booms be placed at Kring Point to divert the floating oil from the Goose Bay marsh area followed by deploying booms to protect Chippewa Bay and associated marsh areas.

- Recommendation for mitigating the effects of the spill on specific populations.

For the NEPCO 140 spill, specific steps were recommended and approved by the OSC and Response Team for protecting unoiled waterfowl populations and cleaning those birds already contaminated. These included setting up booms with helium filled balloons attached to divert birds from the oiled areas plus establishing a fully equipped and professionally staffed center for cleaning oiled waterfowl.

Figure 4. DEC Biologists cleaning oiled Canada Geese at Wilson Hill Refuge .

The DEC biologists established a diet supplement and maintenance program for orphaned Great Blue Heron fleglings whose parents were entrapped in the oil. This program involved placement of tubs of alewives obtained from a local bait supplier on Ironside Island. The DEC placed NO TRESPASSING signs and maintained a vigilance around the island to discourage "sightseers" and "well-meaning" citizens.

- Recommendations as to types of clean-up operations that would be most effective and least damaging to the environment. For example, oiled marsh plants may be left to be washed by currents or tidal action in locations where conditions are optimal for this to occur. In other instances, it may be better to diminish effects to populations by cutting or cropping oiled grasses.

Figure 5. Cropped Oiled Marshes in Chippewa Bay, St. Lawrence River

An intensive marsh grass cutting and removal operation was initiated and maintained during the NEPCO 140 spill to:

- Diminish contamination potential for those marsh animals not initially affected, particularly those populations like muskrats that move back and forth from the water to the marsh interior.

- Diminish the chance of further water quality impact from oil "bleed off" from the plants during warm weather.

As previously indicated, the NEPCO 140 was unique in that biologists at both the federal and state levels worked closely together to provide valuable information and recommendations to the OSC and Response Team. It turned out that as the clean up progressed, the OSC solicited additional information and advice as economic pressures began to affect the operation. In responding to this request, a priority scheme was developed through consensus and provided to the OSC. This was accomplished by the URS Company, San Mateo CA. under contract to the EPA. URS personell interviewed key resource managers, assembled the information and developed the format for a priority scheme which was then provided to the OSC and Response Team. This information was especially useful to the OSC for making decisions relative to further clean-up operations.

An important issue which evolved out of the initial biological assessment activities was the question of long term impact to the marsh populations and water quality. The International Response Team recommended that studies be conducted to investigate possible damage to these populations and adverse impact to the economy of the Thousand Island region due to the oil spill. The objectives and expected benefits are as follows:

OBJECTIVES

1. To evaluate clean-up relative to the environmental impact of the oil spill.

2. To determine the effects of the spill on natural populations and resources.

3. To determine the levels of residue petroleum hydrocarbon compounds within the affected ecosystems.

4. LASTLY, but most impartant, to synthesize the findings from the above into a usable form.

RESULTS/BENEFITS EXPECTED

1. Development of a body of knowledge which can be utilized by decision makers within various governmental and planning agencies.

2. Information generated will be utilized by Canadian and United States agencies involved in oil spill clean-up and contingency planning.

3. Ultimately these agencies will be better able to reduce negative environmental and economic impact of spilled oil.

In summary, biologists from resource management agencies can and should play a crucial role in the decision making scheme that is utilized in managing oil spill clean-up. As illustrated in the NEPCO 140 spill, state and federal agency biologists worked in concert to provide the International Response Team and OSC with technical information and recommendations that were used in setting priorities and implementing mitigative measures for the most expensive clean-up effort of all spills to date.

In this age of tightening budgets and staff limitations coupled with additional legislative mandates to be implemented, cooperative effort is vital and essential. In the most recent amendments of the Federal Water Pollution Control Act, damage to natural resources from oil and hazardous materials must be evaluated, followed by restoration. As stewards of our nation's natural resources, these new mandates present new challenges and tasks on both state and federal resource management agencies. To meet these changes, working professionals, especially biologists, should work together in performing damage assessment studies which will ultimately be used in providing further protection of these resources and environment.

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THE NEPCO 140 OIL SPILL

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THE NEPCO 140 OIL SPILL

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The NEPCO 140 oil spill occurred at the beginning of the tourist season in the Thousand Island region of the St. Lawrence River on 23 June 1976. Due to the inaccessibility and irregular shoreline, clean up was extremely difficult requiring inordinate amounts of hand labor to accomplish the desired level of clean up thus causing the NEPCO 140 spill to be the most expensive to date.

The NEPCO 140 had been plying the waters of the St. Lawrence River and Great Lakes for several years before it grounded in the American Narrows of the St. Lawrence River on 23 June 1976. It was a warm, slightly foggy evening with a slight southwesterly breeze. At 1:38 AM, the Coast Guard at Alexandria Bay, New York received a radio call from the tug EILEEN C pushing the NEPCO 140 that they had run aground on Comfort Shoal and ruptured an aft peak tank.

Although the volume of oil (308,000 gals) was not large, it was still classified as a major spill according to USCG-EPA criteria. The type of oil (No. 6) was extremely important being that it quickly covered the river and then weathered into a black adhesive residue that clung tenaciously to all the environmental substrates it encountered; birds, rocks, docks, boats, floats, plants, ramps and people. The clean-up costs for removing oil from these surfaces was the most ever incurred for any spill to date, $8.5 million from the time of the spill to mid-October 1976.

The main reason for constructing the St. Lawrence Seaway was to allow the transport of commodity materials by ocean going vessels. Since its opening, ship traffic and tonnage has increased to the present bulk of more than 54 million tons carried by 4350 ships for 1976 (SLEOC, 1977).

TABLE 1.

SELECTED TRAFFIC SUMMARY
from Montreal to Lake Ontario
CARGO (in millions of tons)

	General	Bulk	Total
1964	3.7	35.6	39.3
1965	5.6	37.8	43.4
1966	5.5	43.7	49.2
1967	6.0	38.0	44.0
1968	8.0	40.0	48.0
1969	7.0	34.0	41.0
1970	6.5	44.6	51.1
1971	8.6	44.3	52.9
1972	7.9	45.8	53.7
1973	5.8	51.8	57.6
1974	4.5	39.6	44.1
1975	3.6	44.4	48.0
1976	4.5	49.8	54.3

Source: St. Lawrence-Eastern Ontario Commission 1977.

The potential for an oil spill is omnipresent as illustrated by the spills which have occurred prior to and since the NEPCO 140. Although none have matched the NEPCO 140 in volume and extent of contamination, oil spills are likely to increase with the number of vessels using the seaway.

The foremost reason which made the NEPCO 140 so extraordinary is the area that was affected by the spill. In fact, by all standards, it could not have occurred at a worse place (Foley, 1977). The Thousand Island region is a high multiple use area with an emphasis towards water-oriented activities. These uses translate into a variety of interests, both private and public that were affected by the spill.

TOURISM

Alexandria Bay is the heart of the American section of the

Thousand Islands which are a world renown tourist attraction. This area is shared by the United States and Canada as the boundary passes through the island region. An event like the NEPCO 140 spill immediately generates international concern and anxieties. The fact that the spill originated on the American side placed the primacy role established in the U.S.-Canadian Oil Spill Contingency Response agreement on the U.S. Coast Guard, Ninth District.

Tourism is considered to be the areas leading industry and is substantiated by the large numbers of people that come to the area to engage in tourist activities. Even the relatively short season does not seem to discourage visitors because the area is in proximity to the Adirondacks and Finger Lakes and is within a reasonable driving time from major U.S. and Canadian urban areas.

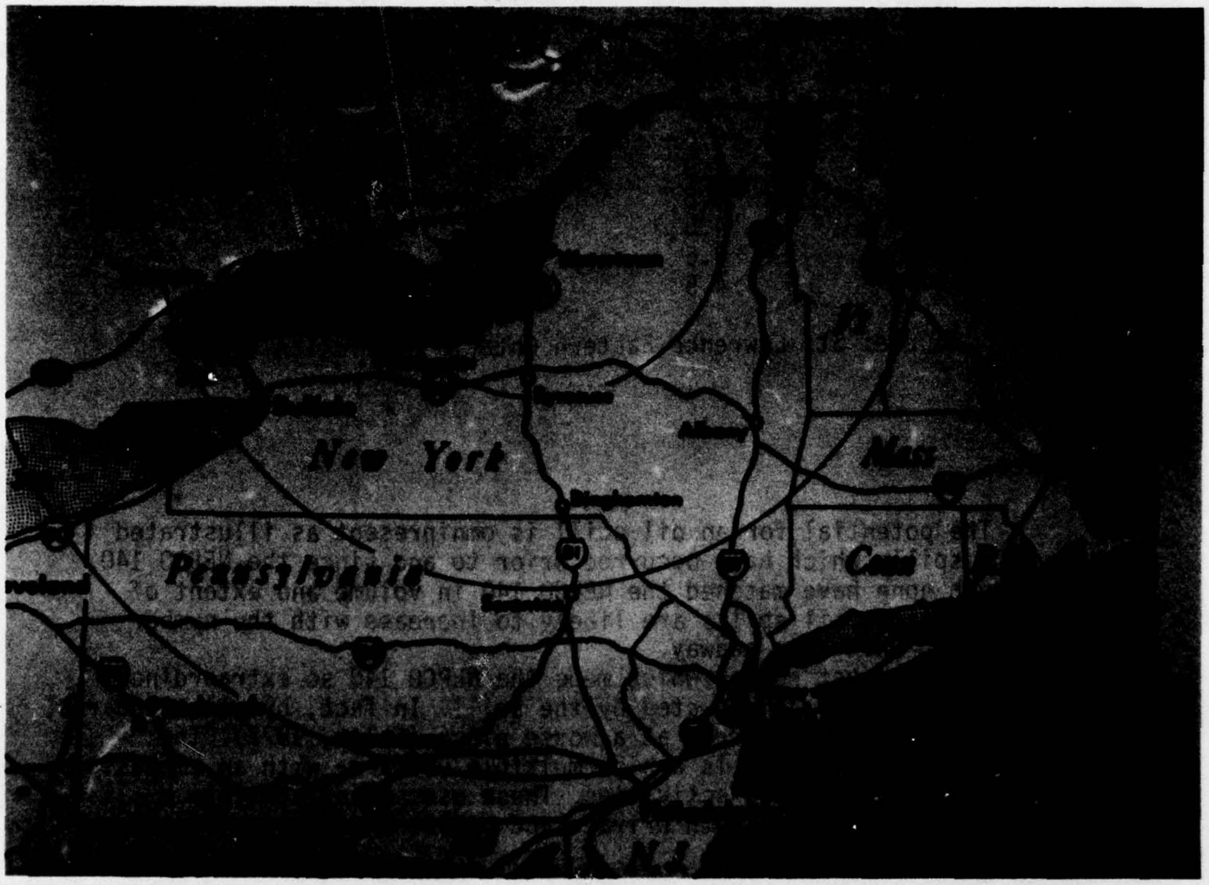
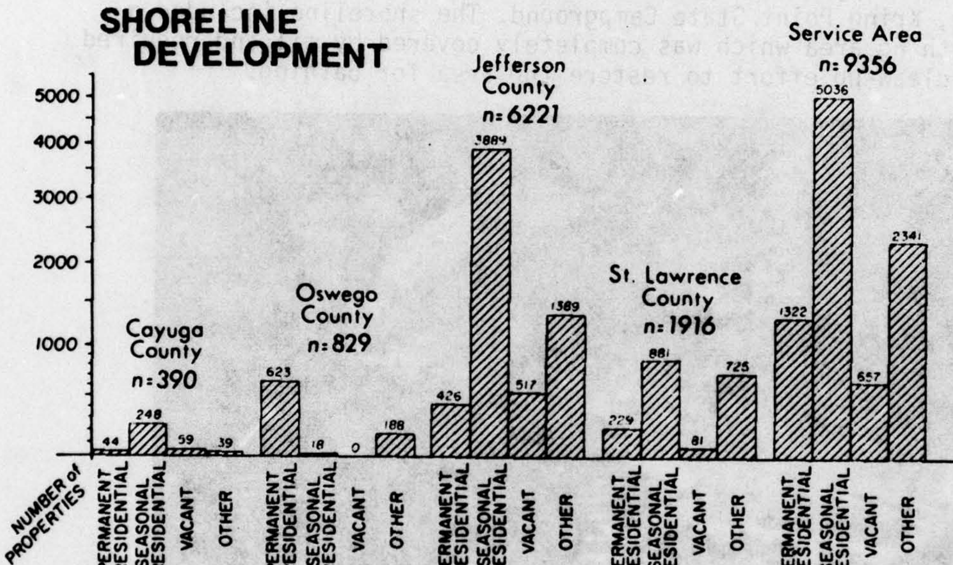


Figure 1. Proximity of 1000 Island Region to Urban Areas. (by permission)

WATERFRONT HOME OWNERS

Most of the shoreline of the mainland and many of the islands are privately owned by people who spend a portion or their entire summer at these residences. In fact, in Jefferson County which encompasses a large portion of the Thousand Island region, seasonal residential properties outnumber all of the other type of properties combined (SLEOC, 1977).

Figure 2.



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RECREATIONAL INTERESTS

Most of the people who visit the Thousand Island region other then the sightseers, come to the area for the following activities:

Sports Fishing

A major attraction to the area is the abundance of sports fish populations. The Thousand Island region is noted for its large-

mouth and smallmouth bass, northern and walleye pike and muskelunge fishing. More fishing licenses are sold in Jefferson County than any of the surrounding counties within the St. Lawrence-Eastern Lake Ontario area (SLEOC, 1977). Sports fishing in this area is a multi-million dollar resource from all of the sales and support services utilized by the fishermen. The apprehension that was caused by this spill which occurred at the height of the bass fishing season was vocalized by the boat rental operators, fishing gear merchants and marina operators plus the fishermen themselves.

Camping

Camping in the Thousand Island region is a sole activity or is performed in conjunction with another activity like fishing or boating. Within the four townships affected by the spill, exists a total of 66 campgrounds which can accomodate over 15,000 campers. One of the campgrounds affected was a state-owned and operated facility, Kring Point State Campground. The shoreline included a small bathing area which was completely covered by oil and required a major clean-up effort to restore the area for bathing.

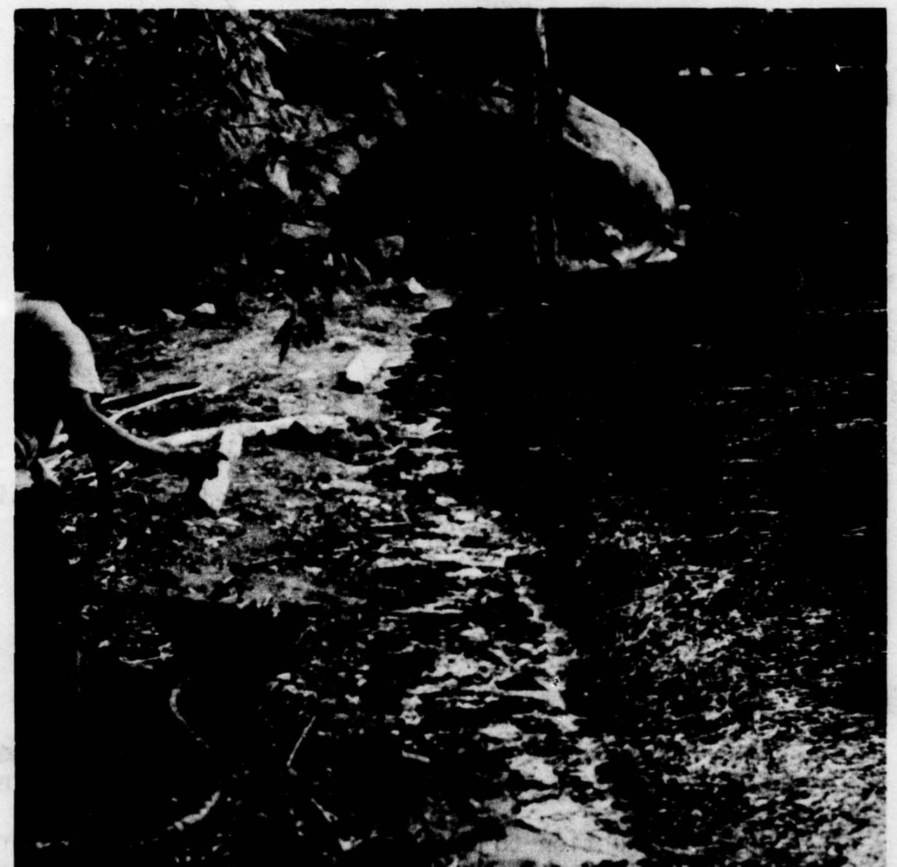

Figure 3. Oiled Bathing Area-Kring Point State Park

Boating

Boating, as an activity, rates high as most all of the seasonal home owners own and operate boats. Speed boat racing is popular on both the Canadian and United States sides. During the early days of the spill, the seaway was closed to all watercraft. However, boating was allowed after the oil had blown ashore. Most of the boats in the water at the time of the spill became heavily contaminated from the floating oil.

Sightseeing

The sightseeing attractions are the rugged beauty of the islands as a geological feature and the homes on the individual islands; all of which require a boat trip to appreciate these sites.

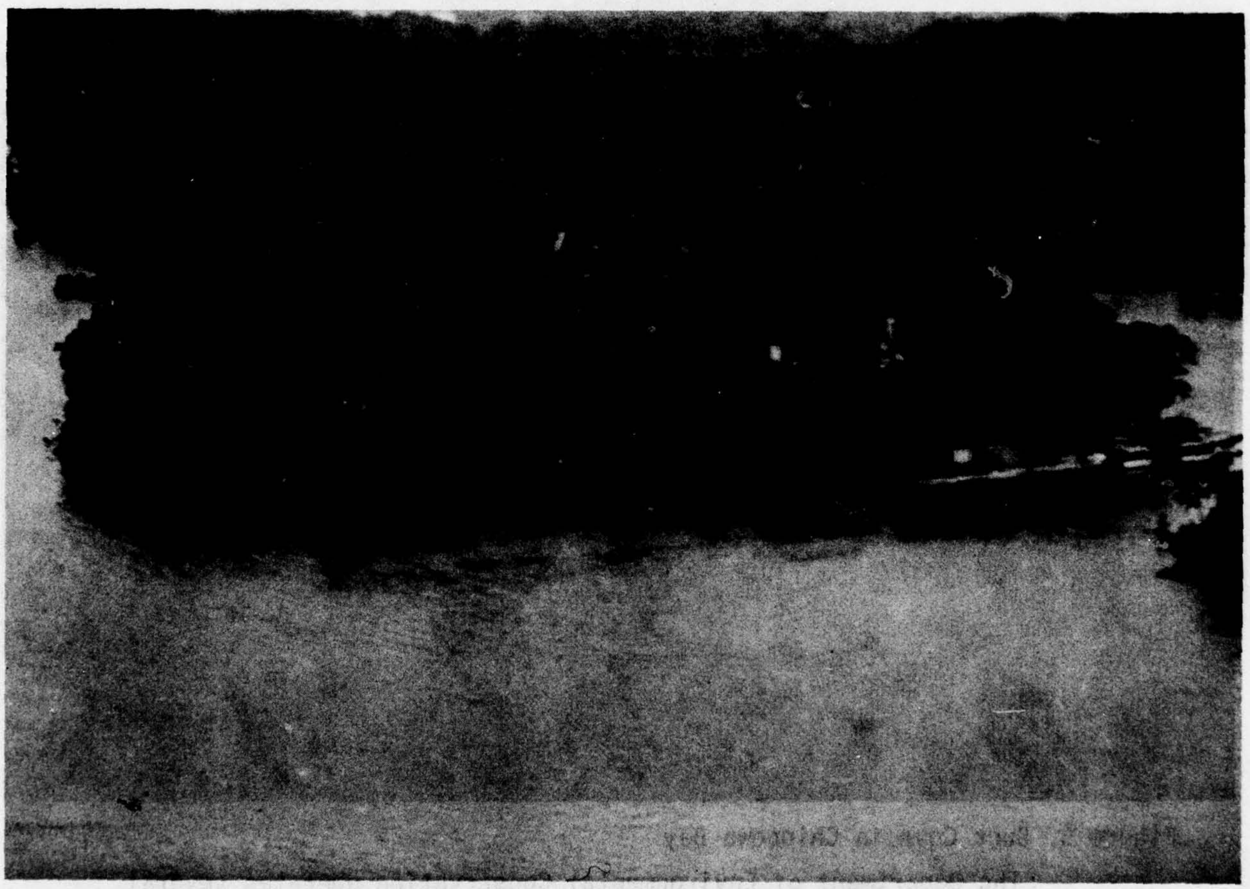

Figure 4. Bolt Castle on Heart Island in the American Thousand Islands

While the river was closed to boat traffic, all sightseeing activities ceased. Soon after, an outcry was heard from the townspeople and sightseeing boat owners as to the effect the spill was having on their livilihood.

Non-seasonal (year round) Activities

Fur trapping and waterfowl hunting are the two activities which occur during the fall and winter months. Much concern was shown as to the impact that the spill would have on these populations and their habitats. The river shoreline is riddled with bays and coves, many of which have extensive fresh-water wetlands at the mouths of the tributary streams feeding into the St. Lawrence. These areas serve as breeding, hatching, spawning and nursery areas for a multitude of native and migratory species which support hunting and fishing throughout the year.

Figure 5. Duck Cove in Chippewa Bay

The Department of Environmental Conservation operates several wildlife management areas, one of which was impacted by the oil spill. Hunting is allowed on a regulated basis within these areas, however hunting is not restricted to state lands in so far as much of the privately owned lands are in a natural state and provide good hunting conditions.

OVERALL ENVIRONMENTAL QUALITY

By all standards the environmental quality for this area of New York State is considered to be superior. The State Water Quality Classification for the St. Lawrence-Eastern Lake Ontario reflects the multiple uses for the water resources of the region. The

TABLE 2. **CLASSIFICATION OF COASTAL WATERS AND TRIBUTARY STREAMS in the St. Lawrence-Eastern Ontario Area***

Class	Water Body	Best Usage
A-Special (International Boundary waters)	Lake Ontario and St. Lawrence River (and their bays and inlets except where noted otherwise)	1. Water supply 2. Primary contact recreation 3. Any other
B	Little Sodus Bay, The Pond, North Pond	1. Primary contact recreation 2. Other than water supply
C	Rice Creek, Oswego River, Oswego Harbor, Catfish Creek, Little Salmon River, Snake Creek, Grindstone Creek, Salmon River, Deer Creek, Little Sandy Creek, South Pond, Lindsey Creek, Skinner Creek, South Sandy Creek, Goose Pond, Floodwood Pond, Sandy Creek, Lakeview Pond, Little Stony Creek, Black Pond, Stony Creek, Black River Bay, Black River, Perch River, Chaumont River, Kent's Creek, French Creek, Otter Creek, Cranberry Creek, Crooked Creek, Chippewa Creek, Oswegatchie River, Sucker Brook, Coles Creek, Grass River, Raquette River	1. Fishing 2. Other than water supply and primary contact recreation
D	All other tributaries	1. Secondary contact recreation (fish will survive, but can not propogate)

*In effect January 1977. For tributaries, the indicated classification is that of their lowermost segments (where they enter the lake or river). Portions of the upper reaches of these streams, and their branches, in many cases have other (higher or lower) classifications. Classifications are reviewed, and may be revised, every three years.

Source: NYS Department of Environmental Conservation, Water Quality Standards Section.

waters are classified as A Special which reflect the international importance given to the St. Lawrence River as boundary waters. A Class A designation by New York State indicates that the waters can be used as a water supply, primary contact recreation and any other use, including fishing.

SYNOPSIS

The NEPCO 140 oil spill is considered as one of the most extraordinary spills from the standpoint of the interest expressed by the local populace concerned for the impact of the spill on their

livelihoods and recreation; the concern for the public resource agencies for the impact of the spill upon the native and migratory and natural habitats; the recreation area managers, both private and public, concerned for the impact on recreation; the St. Lawrence Seaway Development Corporation concerned for the impact on river navigation. The international aspect was a major concern and would have been greater had more Canadian shoreline been contaminated.

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THE ECOLOGICAL IMPACT OF BUNKER C OIL ON FISH AND WILDLIFE IN ST. LAWRENCE RIVER MARSHES

A PRELIMINARY REPORT

Maurice M. Alexander
Patricia Longabucco
David Phillips

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THE ECOLOGICAL IMPACT OF BUNKER C OIL ON FISH AND WILDLIFE IN ST. LAWRENCE RIVER MARSHES

A PRELIMINARY REPORT

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ABSTRACT

Marshes and bays of the St. Lawrence River were impacted to varying degrees with Bunker C oil from NEPCO-140 barge on June 23, 1976. In spite of an effective cleanup, losses of fish and wildlife were great.

A two-year study was established for the 1977 and 1978 seasons to investigate fish and wildlife changes, and the presence, movements or accumulation of petroleum hydrocarbons.

This report reviews the basic characteristics of the spill, the environment, the initial impact on fish and wildlife and the cleanup. It presents the results of the first season's study of fish and waterfowl at seven locations having variable degrees of impaction from none to heavy.

It appears that natural biota may have a remarkable capacity to recover under the specific conditions of this spill. However, a second season's data and the chemical analyses are needed to properly assess the long range impact.

INTRODUCTION

The Thousand Islands Region of the St. Lawrence River is famous for its fish and wildlife resources, and the sporting opportunities they provide. The value of these resources has been estimated at several million dollars. Numerous bays with extensive marshes exist in this section of the river. These shallow bays are very productive of fish, as are the marshes productive of ducks and muskrats (<u>Ondatra</u>

zibethicus).

The river proper is deep with rocky shorelines and includes many islands and shoals. In the early morning hours of June 23, 1976 the barge NEPCO-140 hit a shoal where the shipping lane of the St. Lawrence Seaway is close to the United States shore and upstream to a series of bays. The swift current in the channel carried 308,000 gallons of Bunker C oil downstream past these bays and marshes within a few hours. Wave action was dampened by the heavy oil and a banding of 20-25 cm in width occurred along vertical rocks at the shore. However, where the shore was more gradual or the water shallow, a wider zone was impacted. Marshes were very vulnerable. Because of the wind direction, channel currents and the flow-through characteristics of the different bays, the degree of oil impaction upon the marshes varied from slight to heavy, even within a single bay.

Water levels in 1976 were about 0.5 m above normal. This caused the outer edge of the marshes to lie in water more than 0.5 m, except where the mat was floating. In areas where emergent vegetation was sparce or composed of weak-stemmed species such as bulrush (Scirpus spp.), the oil overrode the marsh. However, most of the marsh edge was dominated by cattail (Typha spp.) into which the penetration of oil averaged 3-4 m. Penetration was limited because of the strength and density of the cattail stems, a windrow of debris or floating European frogbit (Hydrocharis morus-ranae) and the thickness of the oil, although a surface sheen of lighter oil components did penetrate farther.

The outer edge of the marsh is a zone of intensive animal activity. Broods of ducks move in and out of the vegetation, as do muskrats, snakes and many other species. It is an area of concentrated feeding by herons, fish, turtles and frogs.

The immediate effect of the oil upon the fish and wildlife was alarming. Although surveys of dead and moribund wildlife were incomplete and difficult to interpret (Smith 1976), it was estimated that thousands were lost during the initial days of the spill. Fortunately the early reproductive period for many species was past. One duck nest was found. It was heavily oiled from the feathers of the incubating hen. The chances for these eggs to hatch and the young to survive is now known to be very slim (Albers 1977).

The Division of Fish and Wildlife established two cleaning stations for wildlife. Although it is hoped that some of the Canada geese (Branta canadensis) were saved, all efforts to save great blue herons (Ardea herodias) failed. It was estimated that up to one-third of the adult population of herons could have been lost (Thomas Brown, Personal communication). This was particularly critical since the young herons had hatched and were in the process of leaving their nests. The major rookery of the area was Ironsides Island, owned by Nature Conservancy. Fish and wildlife personnel periodically placed alewives on the island for these young. Just how successful this activity was could not be measured.

The cleaning or rehabilitation of aquatic birds has been attempted for about every oil spill known from Torrey Canyon to the present (Smith 1975). Most oiled birds are not found and therefore die. Boesch et al. (1974) estimate that only 5-15% of oiled ducks reach shore after a marine spill. Of those that are captured and cleaned, few survive for several reasons. The importance of correctly applying suitable cleaning agents has been stressed (Berkner et al. 1977). In spite of all the efforts taken, mortality rates remain high. Therefore, the immediate effect of oil spills on wildlife is extensive and dramatic in freshwater environments, much the same as in marine environments.

This spill was believed to be the first major one in freshwater environments where follow-up studies were made. An earlier spill in Lake Champlain during the winter of 1971 involving 44,000 gallons of No. 6 fuel oil was cleaned through five feet of ice (Lamp'l 1973). No known follow-up study was made.

A search was made in the literature to learn what the fate of oil might be in a riverine marsh environment. Little was found on the subject. Based on the general coverage contained in Petroleum in the Marine Environment published by the National Academy of Sciences (1975) it seemed feasible that in freshwater as in marine environments, oil could similarly dissolve, evaporate, particulate and settle or oxidize either photochemically or microbiologically. The recent publications on Fate and Effects of Petroleum Hydrocarbons in Marine Organisms and Ecosystems (Wolfe 1977) and Volume 1 of Effects of Petroleum on Arctic and Subarctic Marine Environments and Organisms (Malins 1977) have reviewed our knowledge of what happens to oil after spillage. Although the fate of oil in a freshwater environment was not an objective of this study, the subject is closely related and cannot be ignored.

It was believed that losses to the spilled oil due to dissolving and evaporation were small prior to the time it reached marshes in the bays. The oil had been on the cold river waters for only a few hours of darkness. The cleanup of the marshes began quickly with the oiled marsh plants being cut and removed along with any remaining oil on the surface. Although reports were received that tar balls had been observed in Canadian waters, these could not be verified. None were found in the impacted bays. It was not known how much of the oil was oxidized and/or settled as particulate materials, along with some nitrogen-sulfur-oxygen compounds. However, it did seem possible that through one or more of these oil fate processes, some of the component hydrocarbons could have entered the biological community of the marshes.

It is the purpose of this investigation to determine the more long-range effects of residual oil in the marsh environments in this freshwater system, with particular reference to the fish and wildlife. The project began in the fall of 1977 and will continue through the summer of 1978. There are two parts to this ecological study; one involving population and community analyses, the other involving chemical analyses.

The objectives of the biological aspect of the study are to measure species diversity at sites having varying degrees of impaction, and to compare abundance levels for the more common species of fish and wildlife.

The objectives of the chemical aspect of the study are to determine if there are any polynuclear aromatic hydrocarbons attributable to the spill present in the ecosystem, and if so, to assess their movement, pathways and possible accumulation in various species and/or tissues.

This report will deal with preliminary results of the first year's field ecology studies for fish and wildlife. It would be premature to report on the chemical studies since these data are in various stages of analysis.

STUDY PLAN AND PROCEDURES

The St. Lawrence River system has received very little biological study. The most recent data are those compiled in 1976, preliminary to an extended navigation feasibility study (Geis 1977). No specific data for fish and wildlife are available for the impacted bays and marshes. Any assessment of the ecological impact of this oil spill, therefore, must depend upon simultaneous study of similar unoiled areas.

Seven cattail marshes were selected for study, each large enough to contain its own distinct community of fish and wildlife. Marshes having been heavily, moderately and slightly impacted with the Bunker C oil were located in each of two large bays. The seventh area was located upstream from the spill site and served as the primary control. Limited sampling of mud and cattail roots for chemical analysis was carried out in the fall of 1976. However, the fall shifts in the location of fish and wildlife populations prevented meaningful study at that time.

Water levels during 1977 were about normal which was approximately 0.5 m lower than in 1976.

Major emphasis during the 1977 season was placed on fish and waterfowl, with a limited study of muskrats and only casual observation of other birds, reptiles and amphibians recorded.

Fish were sampled through the use of three types of nets and traps, as they became available. These included twelve minnow traps placed at the edge of the marsh, four gill nets set in front of the marsh and a South Dakota trap net stationed farther into the bay. The gill nets were each 2 m deep and 8 m long. There was one each with 1.2, 2.5, 3.7 and 5 cm mesh size. The trap net had a 16 m leader and 8 m wings. Its mesh size was 2.5 cm.

In this manner most sizes of fish were sampled, with emphasis on the smaller age classes. The nets were fished for 8-12 hours and

then moved. A system of rotating the sampling effort between the seven study areas was developed. All fish captured were identified, measured and marked before releasing. Each of the seven study areas were sampled nine times during the 1977 season.

The waterfowl were sampled through the use of two funnel duck traps at each study area. These were left in place during the summer period, although all were not in operation at a given time. Each trap was 2x2 m by 1.3 m high, made of 2.5 x 5.0 cm wire mesh with the floor and roof of netting. In this manner injury to the birds was minimal. A holding cage at the rear made capture for study and handling easy. The traps were kept baited with cracked corn even when not set.

Captured ducks were marked by species with nasal saddles, the color and number on each assigned by the U.S. Fish and Wildlife Service. This allowed the continued identification of birds seen as well as retrapped during the season. This was also useful in identifying broods with marked hens. Each bird was sexed and aged. The age class of juveniles was determined according to the system of Gallop and Marshall (1954).

RESULTS FOR 1977

Fish

Several potential effects of oil spills on fish have been considered by researchers and some have been studied. These include direct mortality, larval mortality at spawning sites, the interference of reproduction, and the changing of diets after loss of normal food types.

Studies have shown that some adult fish are capable of avoiding petroleum compounds while others cannot (Shelford 1917; Summerfelt and Lewis 1967). There are indications that some fish will utilize oiled invertebrates since they are easier to catch (Blackman and Mackie 1974). On the other hand, the feeding response may be reduced (Korn et al. 1976). The effect of oil on eggs, larvae and juvenile fish probably has been studied most under experimental conditions (Kuhnhold 1970).

This study compares natural populations of fish at the edge of marshes that had been impacted by Bunker C oil to varying degrees. A total of 3,728 fish were captured on the seven areas as given in Table 1. The minnow-trap catch represents fish at the marsh edge, whereas the gill and trap nets represent the open water (normally with submerged vegetation) in front of the marsh. The trap net usually accounted for two-thirds of the latter group. The trap and gill nets caught fish 75-600 mm in length, with the gill nets catching the more extreme sizes. The minnow traps caught mostly young fish 30-100 mm in length. There appears to be no correlation of oil impaction with fish numbers taken in the gill and trap nets. However, for the minnow traps there is a suggestion that the heaviest oiled areas may have reduced larval fish populations. One of these areas, Sheepshead, had essentially no submerged vegetation, whereas the other, Marguerite, had extensive sub-

Table 1

Fish Catch, 1977, St. Lawrence River

Area	Condition	Minnow Traps	Gill Nets S.D. Trap[4]	Total
French	Control	164	452	616
Cranberry	Slightly Oiled	201	388	589
Crooked	Slightly Oiled	125	346	471
Kring[1]	Moderately Oiled	143	362	505
Chippewa[2]	Moderately Oiled	232	454	686
Marguerite	Heavily Oiled	58	462	520
Sheepshead[3]	Heavily Oiled	26	315	341
Totals		949	2779	3728

[1]-Encrusted surface layer due to pollution

[2]-Most extensive submerged vegetation

[3]-Least amount of submerged vegetation

[4]-S.D. Trap = South Dakota Trap Net

merged vegetation. The area with heaviest submerged vegetation, Chippewa, was moderately oiled and had the largest catch in the minnow traps. The question as to whether the submerged vegetation or the oil had the greatest effect on the smallest fish sizes compounds the problem and needs further study.

Table 2 gives the number of species captured on each area. The two areas with the lowest number of species (13) were heavily and moderately oiled. The highest number of species (19) was recorded for a moderately oiled area. The other areas were rather uniform (15 or 16). Species diversity indices were calculated using the Shannon-Weiner formula for H' (MacArthur and MacArthur 1961), as well as Pielou's evenness (J') (Pielou 1966). Based on a 95% confidence interval, only one area had a significant difference, this being the heavily oiled area with the least amount of submerged vegetation, Sheepshead. This could be attributed, in part, to the greater evenness between species caused by less dominance of pumpkinseed (Lepomis gibbosus).

No population estimates could be calculated because of the small number of recaptures. The total number caught in each area should be a fair index of abundance since the sampling effort was essentially uniform.

Data for the brown bullhead (Ictalurus nebulosus), pumpkinseed, yellow perch (Perca flavescens), golden shiner (Notemigonus crysoleucas) and largemouth bass (Micropterus salmoides) were examined in detail. Only the largemouth bass gave any indication of having a population difference that could be related to the degree of oiling (Table 3). The catch of largemouth bass in the minnow traps seems not to have included any age class other than the young of the year. Their size increased progressively during the season from 25 mm in June to 100 mm in September. This compares favorably with size measurements taken by Kramer and Smith (1960) in Minnesota. Their data show a similar increase in young of the year from 35 mm in July to 84 mm in August. The gill nets and the trap net did not take bass under 100 mm in size. Specific ages are being determined by scale readings in 1978. The control area had a high ratio of young of the year to older fish, the slightly oiled areas had an even distribution of the two age groups, while the moderately and heavily oiled areas had a low ratio of young of the year to older fish. The exception was the moderately oiled area that had the greatest submerged vegetation and the greatest species diversity, Chippewa.

Caution should be used in drawing conclusions since it is known that largemouth bass survival is influenced by a variety of conditions (Shirley and Andrews 1977). The stage most susceptible to oil may be after the yolk sac is resorbed and external feeding begins (Kuhnhold 1970). If this is the case, the lack of largemouth bass fry in the more impacted areas could be related to the timing of spawning and development with the oil spill or its sensitivity to certain residual compounds. This is being studied further in 1978.

Table 2

Fish Species Diversity, 1977, St. Lawrence River

Area	Condition	Richness[4] S	Evenness[5] J'	Diversity[6] H'
French	Control	15	.6059	1.6409
Cranberry	Slightly Oiled	16	.5627	1.5601
Crooked	Slightly Oiled	16	.5984	1.6591
Kring[1]	Moderately Oiled	13	.5393	1.3833
Chippewa[2]	Moderately Oiled	19	.6083	1.7912
Marguerite	Heavily Oiled	13	.6338	1.6257
Sheepshead[3]	Heavily Oiled	16	.7295	2.0225*

[1]-Encrusted surface layer due to pollution

[2]-Most extensive submerged vegetation

[3]-Least amount of submerged vegetation

[4]-Richness (S) = No. of Species

[5]-Evenness (J') = H'/H Max (Pielou)

[6]-Diversity (H') = $-\sum_{i=1}^{S}$ Pi log Pi (Shannon-Weiner)

Table 3

Largemouth Bass Catch, 1977, St. Lawrence River

Area	Condition	Minnow Trap (young)	Gill Nets S.D. Trap[4] (Older)	Total
French	Control	25	1	26
Cranberry	Slightly Oiled	12	15	27
Crooked	Slightly Oiled	7	8	15
Kring[1]	Moderately Oiled	0	11	11
Chippewa[2]	Moderately Oiled	30	3	33
Marguerite	Heavily Oiled	0	11	11
Sheepshead[3]	Heavily Oiled	1	3	4
Total		75	52	127

[1]-Encrusted surface layer due to pollution
[2]-Most extensive submerged vegetation
[3]-Least amount of submerged vegetation
[4]-S.D. Trap = South Dakota Trap Net

Waterfowl

The results of previous investigations on the effects of oil on waterfowl indicate that there are two potential impacts. The first is early debilitation or death of individuals, or embryos in eggs being incubated by contaminated hens. The second is toxication following the ingestion of oil or oiled food and the resultant physiological imbalance.

Most of the earlier studies have involved the administering of relatively large doses of oil over a fairly short period of time, reflective of amounts encountered directly after an oil spill (Hartung 1963, 1964, 1965; Hartung and Hunt 1966; Snyder et al. 1973; Kopischke 1972; Grau et al. 1977).

In this study there was an assumed low-level chronic contact of some form with residual oil components over an extended period from spring to fall migration under natural conditions. This period includes the reproduction of the species present and the development of the young.

Ducks were observed at all seven study areas, although live trapping was not successful at two areas and questionable at a third. The two unsuccessful areas included Kring which had a severe encrusting at the marsh edge due to suspected sewage pollution, and Sheepshead where the traps either blew down or were plugged with floating vegetation. Cranberry was the questionable area where the ducks did not respond to bait.

A total of 138 ducks were trapped on the seven areas as given in Table 4. The first number of each fraction indicates the juveniles captured, the second the capture of adults. The areas are listed in the same order as before, unoiled to heaviest oiled. As already stated, only four have usable data, these being the control and one each of lightly, moderately and heavily oiled marshes. Although the greatest trap success occurred on the control area, the second most successful area was one of the heaviest oiled, Marguerite. The remaining slightly and moderately oiled areas were somewhat less successful but about equal.

Observations of all waterfowl seen were recorded whenever the areas were visited. These data although substantial for each area do not give any conclusive trends that can be directly attributed to the presence of oil. Although there may be a suggestion of a decline in birds seen with an increase in oil, the natural variability of areas similarly oiled may invalidate such a suggestion.

Close examination of the data indicated some individual characteristics of the duck species resident on the areas. Species universally present in St. Lawrence marshes were wood duck (Aix sponsa) and mallard (Anas platyrhynchos). Blue-winged teal (Anas discors) and black duck (Anas rubripes) were seen at least once on all but one area (Kring). Others observed on occasion were green-winged teal (Anas carolinensis)

Table 4

Waterfowl Capture, 1977, St. Lawrence River

Area	Condition	Wood Duck	Mallard	Blue-winged Teal	Black Duck	Total	Birds per trap day	Birds per visit
French	Control	5/3[4]	13/3	12/3	1/0	31/9 = 40	0.91	10.71
Cranberry	Slightly Oiled	0/2	2/0	0/0	0/0	2/2 = 4	0.11	7.45
Crooked	Slightly Oiled	7/8	6/2	4/0	0/0	17/10= 27	0.52	3.64
Kring[1]	Moderately Oiled	1/0	0/0	0/0	0/0	1/0 = 1	0.03	8.67
Chippewa[2]	Moderately Oiled	9/5	3/0	6/0	3/0	21/5 = 26	0.50	5.06
Marguerite	Heavily Oiled	7/7	11/3	10/1	0/0	28/11= 39	0.72	5.07
Sheepshead[3]	Heavily Oiled	0/0	1/0	0/0	0/0	1/0 = 1	0.02	4.13
Totals		29/25	36/8	32/4	4/0	101/37	0.57	6.15
		54	44	36	4	138		

[1]-Encrusted surface layer due to pollution
[2]-Most extensive submerged vegetation
[3]-Least amount of submerged vegetation
[4]-Juveniles/Adults

and gadwall (Anas strepera). A pair of Canada geese were present on one area in early summer but did not nest. However, most of the waterfowl data came from three species--wood duck, mallard and blue-winged teal.

The control area, French, had the best duck community based on trap success and sight observations. Mallard and blue-winged teal were the dominant species, probably using adjacent fields for nesting sites. Wood ducks were not abundant because of limited nesting cavities. Brood capture and observation indicated that this area was very productive for ducks.

The two slightly oiled areas, Crooked and Cranberry, had fairly good duck populations, the first being dominated by wood ducks, the second by mallards. This difference reflected the availability of appropriate nesting sites for the two species. In spite of the poor trapping records for Cranberry, it appeared to be more productive than Crooked.

The two moderately oiled areas, Kring and Chippewa, were different in their size and quality of habitat. Kring supported a fairly good population of ducks but specific data were difficult to obtain. Chippewa ducks were well distributed between wood duck, mallard, blue-winged teal and black duck. Broods indicated this area to be very productive for ducks.

The two heavily oiled areas, Marguerite and Sheepshead, were also different in their size and quality. Sheepshead was narrow, exposed and had more interference from campers and predators. However, diversity was greatest since gadwalls and geese were seen there. Still production was very low. In contrast, Marguerite was one of the more productive areas, being somewhat similar to the control area. Wood duck, mallard and blue-winged teal were about equal in abundance, although spatially segregated.

Duck broods did not differ significantly between the study areas. There was the same general trend for brood size reduction as the season progressed. Some broods of 12 were seen in late May and early June. By late July or early August the number was more often four.

A series of ducklings were taken for chemical analysis since their entire life had been spent on the oiled area.

Vegetation

A vegetational sampling procedure was started but time limitations prevented its completion in 1977. Such a study is planned for 1978. In the course of the summer, as the cattail growth continued, it became evident that the marsh edge on moderate to heavily oiled areas was experiencing a more rapid development than other areas or the cattails behind the impacted marsh edge. Reasons for this were considered but the clearest association appeared to be with the oil.

In Chippewa this increased growth phenomenon stopped abruptly where a rather effective boom prevented movement of the oil into the Creek. Later as the cattail heads appeared and matured on most areas, it was noted that no such fruiting took place along the oiled edge. The question could be asked if some of the residual oil components were stimulating growth but preventing seed production. This is being followed closely in 1978.

DISCUSSION

No attempt was made to thoroughly review the extensive research that has been done on the effect of oil on marine organisms. Clark and Finley (1977) reviewed the effects of the various oil spills from Torrey Canyon to Argo Merchant. Both the physical characteristics and the associated biological systems of freshwater environments are vastly different from marine environments. No comparisons have been attempted in this study.

The current study involves the long range effects of a Bunker C spill in a riverine environment having bays and marshes along its course. It is a spill that occurred in mid-June after most of the early reproductive processes were past. In no way can it represent all oil types, all freshwater environments or all times of year.

It would appear from this first year's data that the natural ecological forces in the biological communities of the St. Lawrence River bays and marshes are capable of continuing their stability in the face of perturbation from Bunker C oil when effective cleanup procedures are available. The lack of prior data makes the drawing of specific conclusions hazardous, if not impossible. However, no outstandingly obvious differences in the biotic communities were found one year after the spill that could be positively attributed to the oil alone. Some potential effects such as those relating to young largemouth bass and the growth of cattail need further study. Other suggested correlations such as relationship of waterfowl observations to degree of oiling are weak and not conclusive.

It is recognized that even areas carefully selected for their similarities, are not truly similar. Nature is not so regimented. It is now known that there are physical and biological differences in the study areas that may be equally or possibly even more influential than the oil impaction in determining the characteristics of the fish and wildlife communities.

It was not possible to study all groups of organisms that make up these marsh communities, and this was not our objective. Another year's data will add much to our understanding of the phenomena at work following this spill. When the data are complete on the presence, movement and possible accumulation of petroleum components, such as polynuclear aromatic hydrocarbons, in the food webs, we can look at our data for further interpretations. We feel it is important that

these study areas be monitored over the next several years before a final chapter can be written on the biological after-effects of the 1976 spill of the NEPCO-140.

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Following the 308,000 gallon oil spill on the St. Lawrence River June 23, 1976 the United States Environmental Protection Agency funded efforts to determine the economic and environmental impacts. This article describes the methodology used, problems encountered and findings resulting from the economic impact analyses. The impact area adjacent to the St. Lawrence River is heavily dependent upon the recreation/tourism sector of the economy.

Short term impacts were found to be significantly less than expected to occur following the spill. Over 8.7 million dollars were expended in the clean-up. This more than compensated for the loss to the recreation/ tourism sector due to the spill. The incidence of the impact differed relative to the impact of the recreation/ tourism activity. Longer term economic impacts are indeterminate pending identification of long term environmental impacts.

I. INTRODUCTION

Following the NEPCO 140 grounding on June 23, 1976, an estimated 308,000 gallons of oil were spilled near the upriver end of the Thousand Islands section of the St. Lawrence River. The spill occurred just prior to the opening of the tourism and recreation season. The economic impact of the spill was of extreme concern since the tourism and recreation sector is a significant portion of the economic activity that occurs along the St. Lawrence River (see Figure 1). Since little information existed regarding the economic impact of oil spills in a riverine environment, the U. S. Environmental Protection Agency funded, through the St. Lawrence-Eastern Ontario Commission, a research effort to determine both the economic and environmental

impact of the NEPCO spill.[1] Included in this paper is a discussion of the efforts undertaken in determining the economic impact.

The specific objectives of this paper are 1) to report the methodology used to determine the economic impact, 2) to summarize the economic impact resulting from the spill and 3) to briefly discuss methodological problems encountered in determining the economic impact.

II. IMPACT DETERMINATION

In order to determine the economic impact of the spill a mail survey of all commercial and residential property owners in the impact area was conducted. This included both United States and Canadian owners.

A. Residential

Of the 459 permanent residential property owners contacted, 79.3 percent responded. Of these respondents, 75 percent reported they incurred a cost in clean-up efforts after the June 23 spill.

These costs included 1,313 hours of labor and $9,834 expended primarily for removing oil from docks, boats and the shoreline. Sixty respondents filed insurance claims following the spill. These claims amounted to $86,562.

In addition it was reported that 1,930 people lost the equivalent of 15,611 recreation days following the spill. Inconveniences other than the loss of recreational opportunity were reported by 30.5 percent of the respondents.

Of the 632 owners of seasonal residences surveyed, 533 responded. Of these respondents 87.9 percent indicated they incurred a cost in clean-up efforts following the June 23 spill. These costs included 3,714 hours of labor and $27,460 expended primarily for removing oil from docks, boats and the shoreline. One hundred forty two respondents filed insurance claims following the spill. These claims amounted to $407,157.

In addition it was reported that 21,821 days of recreation were lost by 4,918 people. These and other reported impacts are reflected in Table 1.

B. Commercial

In order to determine the impact of the oil spill on this sector of the economy, a series of questionnaires were developed. Similar questions were asked but were oriented specifically toward different

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[1] "Damage Assessment Studies Following the Alexandria Bay Oil Spill," funded by the U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory. A two year study ending September 23, 1978.

types of enterprise with a potential for being impacted. This included not only those enterprises immediately adjacent to the river but also those inland and dependent on business generated by persons recreating on the river. Included were guide boats, tour boats, marinas, hotels and motels, restaurants, bait and tackle shops, private campgrounds and gasoline stations.

The data reported by guide boat operators indicated that they experienced no significant economic impact as a result of the spill. The average size of parties guided and the number of parties guided did not vary significantly from 1975 to 1976.

Tour boat operators reported a slight increase in the number of passengers in 1976 as compared to 1975. However, sufficient data was not available to determine if there were any changes in the temporal distribution of these numbers (see Table 2).

Insufficient data was received from operators of marinas to base any judgement as to the magnitude of the impact. However, determined from the responses of 4 of 15 marina operators was a 15 percent decrease in revenue from the sale of gas, oil and other supplies as well as a 7 percent increase in the number of boats launched.

Operators of 170 hotels and motels were identified and contacted and 45 percent responded. Their responses indicated that the average occupancy rate for 1975 was 80.5 percent and for 1976 71.0 percent during the tourist season. Eighteen operators indicated they felt the impact of the oil spill was the primary reason for this decrease. Temporal analysis of occupancy rate data indicated that during the 1976 season the rate was above the 1978 seasonal rate for the period June 10-June 23 (64.8 compared to 61.5) and then less during the period June 24-July 7 (62.8 compared to 74.0). This reflects a short term decrease immediately following the oil spill. Records of cancellations indicated that 240 were received with the oil spill given as the reason for cancelling.

On the positive side the responsive operators reported that 472 nights of lodging were provided to personnel working on the clean-up. The remaining 52 establishments reported they did not provide such lodging.

Minimal changes occurred in terms of employment. Reported increases in hours worked totaled 10 weeks of employment while reported decreases in employment totaled 24 weeks of employment.

Data provided by restaurant operators were insufficient to allow quantitative analyses. However, for those questions a response was received little impact was reported as a result of the spill. A similar statement can be made regarding bait and tackle shop operators.

Thirty-two of the 42 operators of private campsites contacted responded. Reported data on occupancy rate reflected that in 1976 occupancy during the June 24 - July 7 period was 74.3 percent while during the June 10 - June 23 period it was 69.5 percent. This is similar to 1975 rates which were 82.4 percent and 74.1 percent for the respective periods. These figures are also consistent with the overall occupancy rates for the two years. Insufficient data relative to the employment impacts was reported to allow analyses.

Operators of gasoline stations reported increases during the period June 10 - June 23, June 23 - July 7 and for the entire tourist season during 1976 as compared to 1975. Inadequate data was provided to determine the impact on employment.

In addition to the mail survey carried out, a telephone survey of other types of riparian commercial enterprises was conducted. Of the 21 enterprises contacted, only one reported any impact. This was related to the continuing presence of oil and no dollar value was attached to this.

C. Other Riparian Properties

Contact with municipal officials along the St. Lawrence River indicated that there were no problems with water supplies as a result of the spill. Efforts to monitor the situation and planning for alternative sources, if required, occurred but no identifiable costs were accounted with these.

Representatives of the power producers on the St. Lawrence River reported that there was no negative impact in terms of costs or loss of production due to the spill. Flows were not reduced and thus no reduction in generated power occurred. Maintenance in excess of normal was not experienced either.

Since the St. Lawrence Seaway is a major transportation system, it was expected that the oil spill would have a distruptive effect on the operation of this system. The St. Lawrence Seaway Development Corporation verified this, reporting that a total of 42 ships were delayed as a result of the spill. The total delay of 393.3 hours increased transit costs an estimated $171,448.

D. Insurance Claims

Following the oil spill numerous claims were filed with the insurers of the NEPCO 140. A total of 543 claims amounting to $81,470 have been settled. The average amount of these settlements was $150.04.

A total of 174 claims amounting to $26,005,352 remain to be settled. In all cases except four, property damage is the sole or one of the reasons given as the basis for the claim.

Included in the unsettled claims is a $21,000,000 suit by the U.S. government. A portion of this (about 8.5 million) is to cover the actual costs incurred in cleaning up the spill. A suit of $25,000 was brought by the Nature Conservancy and the Central New York Chapter of the Nature Conservancy to cover damages to Ironsides Island and to the blue heron population residing there. Other claims were filed by marina and resort operators and owners of seasonal and permanent homes in the impact area.

E. Clean-up Costs

Currently efforts are being undertaken to obtain additional data from the contractors involved in the clean-up. Data on employment, distribution of costs between labor, supplies, overhead, etc., and costs of clean-up by types of shoreline are being sought.

Data provided by the United States Coast Guard indicated that $8,650,242 were paid the contractors performing the clean-up. Access to the documents supporting these clean-up costs was not avilable.

Other aspects of the impact of the oil spill are being examined and a more complete short term impact analyses may be specified when these are complete. The long term economic impact determination is partially dependent upon the findings of the environmental impact. Since the tourism/recreation sector of the economy is heavily dependent upon environmental factors, any impact to these factors will have an implication to the economy.

III. METHODOLOGICAL PROBLEMS

Several major methodological problems were experienced in developing data required to determine the economic impact of the NEPCO 140 grounding on June 23, 1976. The first and most serious is that operators of commercial enterprises were in general unwilling to provide data on employment and revenue in relation to this issue. Unfortunately these are two items of major significance in determining an economic impact. In retrospect, it may have been more efficient for our analysis to obtain the required information by conducting a limited number of personal interviews instead of relying upon a mail survey of the entire population. The limited number of respondents in several of the categories limited the statistical reliability of the reported impact. Since many of the enterprises are small, seasonal, and family operated there may be factors other than unwillingness to respond that influenced the decision not to provide the requested data. If this is the case a change in survey technique would not be helpful.

Secondly, data developed for a specific purpose is usually not capable of being efficiently utilized for another purpose. The case in point is clean-up cost data submitted to the USCG by contractors.

It was developed to ensure that expenditures for this project would be reimbursed. However, with very limited additional effort reference to the specific geographic areas where the costs were incurred could have been included. This would have allowed quantification of costs of cleaning up specific types of shorelines. Without prior knowledge that this would be useful it was not required by the USCG and thus not provided by the contractor.

It is known that complex interrelationships make the isolation and analysis of a single factor costly and time consuming. To answer the question of whether the oil spill influenced recreation activity on the St. Lawrence River, factors such as weather, state of the economy, gasoline prices, water quality problems and other factors had to be considered. Initial comparison of attendance data reflected a change that did not appear sufficient to warrant the additional expense of detailed analyses. Thus the question will exist whether the conclusion that the oil spill did not have significant impact on the number of recreationists is correct or whether by chance the net impact of other factors resulted in this effect.

In summary it should be emphasized that when methodologies for social science research are being developed, extreme care should be taken to ensure that: 1) access to the required data is obtainable; 2) that the data is in a form that permits its use without inordinate expenditures of effort; 3) that the data gathering technique is appropriate, in this case mail survey; and 4) that if a complex relationship is known to exist an adequate level of resources be made available to ensure examination of all likely aspects of the relationship.

None of the above are new or exciting. They are however simple rules often overlooked or neglected. (In the research effort being reported here their role was significant but not of a nature to negate the findings reported.)

IV. IMPLICATIONS TO STUDY FINDINGS

Although several methodological obstructions were encountered in accomplishing the study it is concluded that it was possible to fulfill the objectives of the study. The refinement in quantification desired was not achieved. However estimates of the general magnitude and incidence of the economic impacts were identifiable.

Based upon the analyses to date, the impact of the oil spill on the tourist/recreation section of the economy was not nearly as great as expected. This finding is in relation to employment and revenue concerns. The exact impact is indeterminate but it is estimated to be in terms of a few percent at most.

In terms of net employment, those employed in oil spill clean-up exceeded those who lost jobs in other sectors. Hence there occurred a net gain in employment in the area as a result of the spill. Data also reflects that most employees were from the area immediately

adjacent to the river.

As hypothesized immediate impacts were more significant than the longer term ones. Pertinent data on cancellations and attendance at state parks reflect that the greatest impact occurred in the week immediately following the spill. After this initial period no discernable reduction in numbers of tourists or recreators was reported.

Although the net economic impact of a 308,000 gallon oil spill was not as severe as many expected it to be, it was a disruptable experience for the area. The expenditure of approximately 8.7 million dollars to clean-up the spilled oil appears to have more than compensated the loss to the tourism and recreation sector. However, it is almost unanimously agreed that cleaning up oil spills is not a desirable activity to base a regional economy on.

In closing it should be noted that this study is more exploratory in nature than definitive. Due to the lack of research efforts regarding this topic this was expected during the period of project formulation.

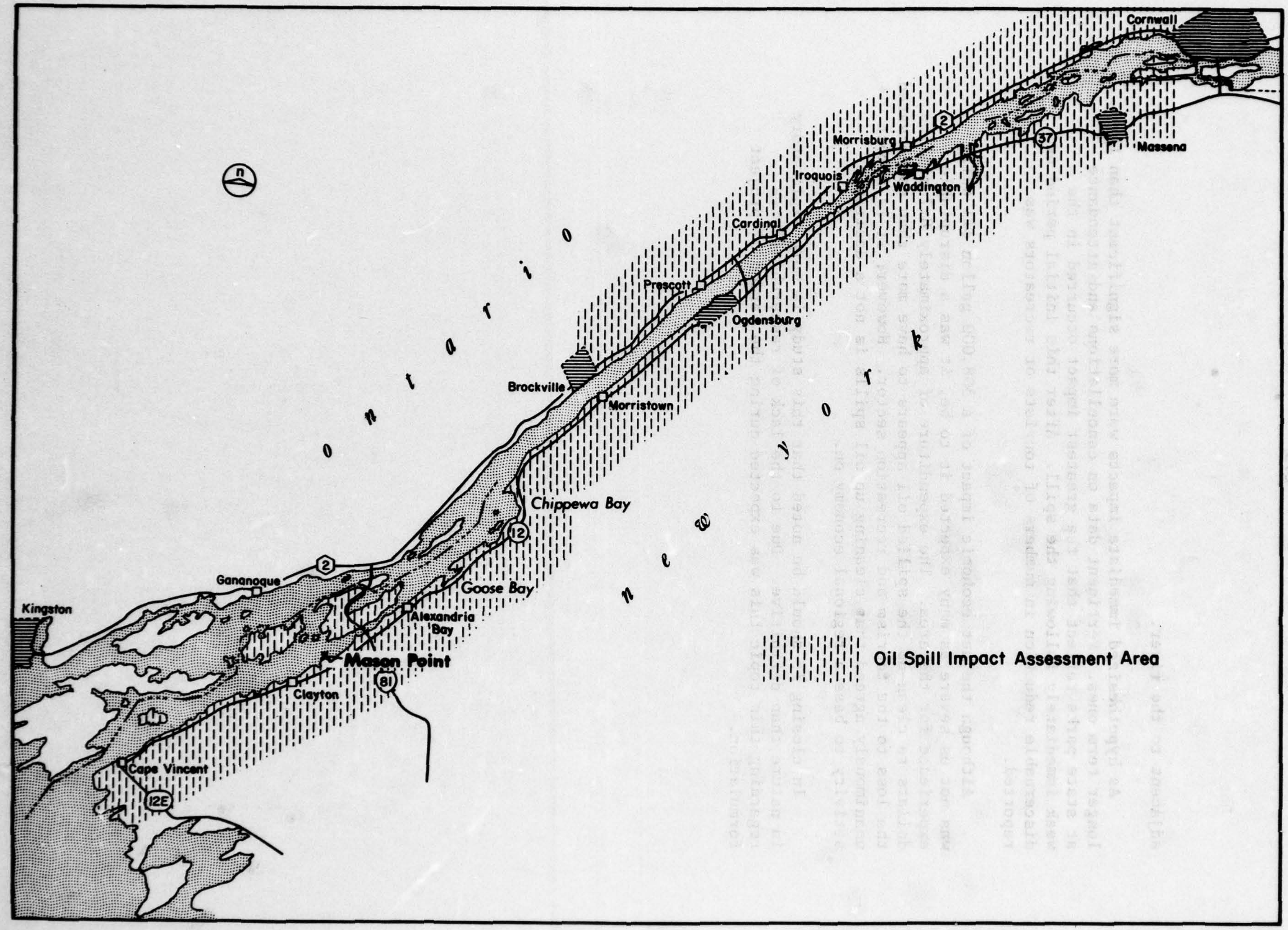

Figure 1. Oil Spill Impact Area.

Table 1. Summary of Residential Impacts

Type of Impact	Residential Property Owners: Permanent, United States		Permanent, Canada		Seasonal, United States		Seasonal, Canada		Total Residential
	Hours	Value	Hours	Value	Hours	Value	Hours	Value	
Clean-up Costs									
Self Supplied Labor	432	1,728	881	3,524	3,067	12,268	647	2,588	
Cost of Item Purchased		7,588		2,246		25,186		2,274	
Total		$9,316		$5,770		$37,454		$4,862	57,202
	United States		Canada		United States		Canada		
	Days	Value			Days	Value			
Recreation Days Lost[b]	15,611	$153,456			21,821	$214,500			$367,956
	United States		Canada		United States		Canada		
	Days	Value			Days	Value			
Other Inconvenience	93	Indeterminate			175	Indeterminate			268 People
Total	$168,542	plus inconvenience to 93 people			$68,326	plus inconvenience to 175 people			$452,158 plus inconvenience to 268 people

[a]These hours reflect the amount of hours of labor the respondent or his family expended. A rate of $4.00 an hours was used to convert the hours reported to dollars. This rate is commensorate with the rate paid to persons working on the clean-up.

[b]A value of $9.83 per day is used to derive a value for recreation days lost. This is based upon data provided regarding expenditures reported in "Characteristics, Perceptions and Attitudes of Resource Users in the St. Lawrence-Eastern Ontario Commission's Service Area," St. Lawrence-Eastern Ontario Commission, 1978.

Table 2. Summary of Reported Commercial/Industrial Impacts[a]

Type of Enterprise	Type of Impact: Positive	Type of Impact: Negative
Guide Boats	None Reported	None Reported
Marinas	None Reported	Sales receipts for gas, oil and other supplies decreased in all time periods.
Hotels/Motels	432 nights of lodging provided to people on clean-up force. $4,980 increase in revenue.	Decrease in occupany rate reported for all time periods. 834 units had a decrease in occupany rate of 9.5% for the 90 day season. This yields a revenue decrease of $75,229 for the summer based on the reported $10.55 per night average rate. The average decrease per establishment was $964. 240 nights of lodging cancelled with the oil spill given as the reason. Decreased revenue $2,532
Restaurants	Receipts up in all periods.[b]	None Reported
Bait and Tackle Shops	(Response not sufficient to report)	
Public Campgrounds	None Reported	Decrease in occupany rate reported for all time periods. 914 sites had a decrease in occupany rate of 8.8 percent for the 90 day season. This yields a revenue decrease of $33,588 for the summer based on the reported $4.64 per night average rate. The average decrease per establishment was $1,018.
Gasoline Stations	Volume sold increased in all periods.[b]	
Other Commercials	None Reported	None Reported

[a]This table covers only those impacts reported via the survey. Many people contacted did not respond because of litigation they were involved in regarding their claim.

[b]This was not reported to be a result of the spill.

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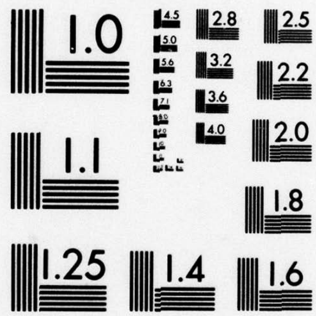
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HIGHLIGHTS REGARDING THE IMPACTS OF OTHER PERTINENT OIL SPILLS (SESSION I)

Chairman: GERALDINE V. COX
American Petroleum Institute

THE EFFECTS OF THE BARGE STC-101 OIL SPILL ON SHALLOW WATER INVERTEBRATES OF LOWER CHESAPEAKE BAY

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THE EFFECTS OF THE BARGE STC-101 OIL SPILL ON SHALLOW WATER INVERTEBRATES OF LOWER CHESAPEAKE BAY

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ABSTRACT

On February 2, 1976, approximately 250,000 gallons of #6 fuel oil were spilled into lower Chesapeake Bay after the Barge STC-101 sank in a storm near the mouth of the Potomac River.

The purpose of this study was to evaluate the effects of the oil spill on benthic macro-invertebrate populations.

Forty stations were sampled along ten transects perpendicular to the shoreline on both eastern and western shores of the Chesapeake Bay. Macroinvertebrate populations were quantitatively examined and sediment particle size analyses were conducted at each station.

A numerical classification technique was applied to the raw invertebrate population data. Normal and inverse analyses were made of quantitative data. A weighted pair-group average clustering technique was applied to both types of analyses.

The results indicated that invertebrate assemblages occurred according to the area sampled. No effects attributable to the oil spill could be detected at the subtidal stations, while intertidal areas may have been damaged to some degree. The shoreline invertebrate populations appear to have escaped any catastrophic damage as a result of the February 1976 oil spill.

INTRODUCTION

On 2 February 1976, approximately 250,000 gallons of #6 fuel oil were spilled into lower Chesapeake Bay from the Barge STC-101 after it sank in a storm near the mouth of the Potomac River. The oil spread over beaches and marsh areas on both eastern and western shores of the Bay. The eastern shore was the most severely affected with hundreds of miles of shoreline coated with tar-like oil. A clean-up effort recovered approximately 167,000 gallons of oil from intertidal areas by scraping beaches and harvesting marsh vegetation. Oil was left on the fragile marsh surfaces and inaccessible subtidal substrates.

The purpose of this study was to evaluate the effects of the spill on benthic macroinvertebrate populations. The shoreline benthos serve an important role in the estuarine food chain as vital food organisms for fish, birds, and larger invertebrate organisms. If this spill had adversely affected the shoreline benthic community, it could have indirectly affected those organisms which feed on them. This type of food chain interruption was the primary stimulus for this investigation.

LITERATURE REVIEW

Petroleum products are toxic to aquatic life. This toxicity may result from smothering of organisms, lethal action of oil fractions dissolved in the water column, or sublethal toxicity which affects the organisms' reproductive capacity. Indirect effects such as the elimination of the animals' food source can also occur. The pathways are presented in Figure 1.

Anderson et. al. (1974) conducted laboratory tests with estuarine fish and invertebrates and various crude oils and refined products. They found that the refined products were more toxic than crude oils. Rossi et. al. (1976) tested polychaete worms against Bunker C oil, #2 fuel oil, and two crude oils. They also found that the refined oils were more toxic than the crudes. The higher mortality in refined products was due to a higher concentration of toxic naphthalene compounds. The naphthalenes are water soluble and affect not only the surface layer and the bottom sediments but the water column between, as well.

Krebs and Burns (1977), investigating a spill of #2 fuel oil, reported that salt-marsh sediments will store oil and that fiddler crabs which inhabit the marsh take up and concentrate hydrocarbons derived from the oil. The reproduction rate of crabs living in the affected marsh was lower than in control marshes. Recovery of normal crab populations in the oiled marsh was not complete 7 years after the spill occurred.

Chan (1973, 1975) investigated the effects of a #6 oil spill on intertidal and shallow water subtidal organisms of the San Francisco area. The spill occurred in January 1971 after a tanker collision. He concluded that the smothering effects of the thick oil was the major cause of mortalities. The oil filled rock crevices and limited habitat available for recolonization. Algal blooms followed as the oil began to break down. By December 1971, the populations of benthos had recovered to normal conditions and no lingering effects were noticed as of April 1974. The recruitment and drift of larval forms was proposed as a major factor in the repopulation of the devastated shorelines.

The National Academy of Science (1973) presented a summary of major oil spills and their biological impacts.

STUDY AREA

Forty stations were sampled along ten transects perpendicular to the shoreline on the eastern and western shores of Chesapeake Bay, Figure 2. These stations were sampled once each from April thru June, 1976. The shoreline in the study area is alternately sand beach and fringing marsh with a shallow, near shore subtidal topography. Because there were no background or pre-spill data on benthic populations in the affected areas, samples were collected from oiled and non-oiled sites with comparable environments. Site environments were sandy beach, tidal creek, and barrier marsh.

On the western shore a sand beach transect north of Windmill Point (A) was sampled as an affected area and an unaffected sand beach near Horn Harbor was selected as a control (C). No intertidal samples were collected on the sand beach transects because the removal of invertebrates with the surface sand during the clean up operation would surely have interfered with our evaluation of the effects of the oil itself. Three samples were collected at each transect at 3, 5, and 10 foot depths on a line perpendicular to shore.

The marsh samples on the western shore were collected from Rigby Island (transect B), where a moderate amount of oil came ashore, and the control marsh at Beach Point (transect D). Samples were collected from the intertidal areas at both of these transects as well as at the 3, 5, and 10 foot depths.

On the eastern shore the severely affected tidal creek area "The Gulf" was examined at five stations on a transect from the intertidal marshes at the creek mouth out beyond the outlying sand bar (transect G). Old Plantation Creek was sampled in a similar manner as a control (transect E).

Transects at Smith Beach (H) and a beach south of the Town of Cape Charles (F) represented oiled and non-oiled sand beaches, respectively. They were sampled as those on the western shore had been, with all stations subtidal at 3, 5, and 10 foot depths.

The eastern shore marsh transects were located at Poles Bluff (J) where heavy concentrations of oil came ashore and at Parkers Marsh (I), which served as a control. Four stations were sampled along both of these transects from intertidal and the 3, 5, and 10 foot deep subtidal areas. The 40 stations are listed in Table 1 according to depth and condition (oiled or control).

Table 1. Station Descriptions.

Depth	Intertidal	3 Feet	5 Feet	10 Feet
Oiled	B1 G1 J1	A1 B2 G2 H1 J2	A2 B3 G3 G4 H2 H3 J3	A3 B4 G5 H4 J4
Control	D1 E1 I1	C1 D2 E2 F1 I2	C2 D3 E2 F2 I3	C3 D4 E4 F3 I4

Stroup and Lynn (1963) summarized 12 years of salinity data for Chesapeake Bay. The seasonal averages for the areas involved in the present study (Windmill Point to Horn Harbor and Parker's Marsh to Old Plantation Creek) are given in Table 2. The seasonal variations in salinity within the study area are not more than 9‰.

Table 2. Seasonal Salinity Averages of Lower Chesapeake Bay.

Season	West (Windmill Point to Horn Harbor)	East (Parker's Marsh to Old Plantation Cr.)
Winter	16-18‰	18-22‰
Spring	13-16‰	16-22‰
Summer	15-19‰	18-24‰
Fall	18-21‰	20-26‰

There was a tendency for salinity on the eastern shore to be higher than on the western shore, due to the Coriolis Effect on flood tide circulation which moves high salinity seawater up the eastern side of the Bay more than the western. The higher volume of freshwater inflow to the western Bay may also play a part in the salinity differences. It was hoped that variations in salinity from station to station would not affect invertebrate population structures nor reduce the validity of comparisons between control and affected transects on the same shore.

METHODS & MATERIALS

The intertidal samples were collected with a coring device made by cutting the bottom out of a 10 x 15cm one gallon paint thinner can. Penetration of the sampler was from 10 to 20 cm. Six cores were collected at each station and composited to yield one square foot sample. The sample was washed in a bucket sieve with a 0.59 mm wire mesh bottom. The material retained by the sieve was preserved in a solution of 10% formalin with Rose Bengal stain. The subtidal stations were sampled with a 6 x 6 inch Ponar grab (15 x 15cm). Four Ponar grabs were taken at each station for a square foot sample. These samples were sieved and preserved as above.

For all samples the organisms were sorted from the debris and identified to the lowest possible taxonomic level. The data are presented in the results section in terms of numbers per square foot of bottom area. Due to inaccuracies involved with the "quantitative" nature of the intertidal sampler and our inexperience in sorting invertebrates from such masses of detritus, the values for intertidal stations may be considered close approximations rather than actual counts.

Sediment samples for particle size analysis were collected at each station. The intertidal samples were collected with a 5 cm diameter core cylinder and the subtidal samples were collected with the Ponar dredge. Each of the samples was homogenized and air dried. They were then shaken through a stack of sieves on a mechanical shaker table. The standard sieves used were the 2.0 mm, 0.42 mm, and 0.063 mm sizes. These divided the particles into four categories; gravel, coarse sand, fine sand, and silt and clay. Results of this analysis were recorded as weight of each fraction and percentage of the total sample weight.

A numerical classification technique which incorporated the Bray-Curtis (1957) dissimilarity measure was applied to the raw invertebrate population data. If n is the number of attributes (species) and X_{1j} and X_{2j} are the values of the j'th attribute for any pair of entities (sites) then the coefficient is:

$$\frac{\sum_{1}^{n} \left| X_{1j} - X_{2j} \right|}{\sum_{1}^{n} (X_{1j} + X_{2j})} \qquad (1)$$

In this coefficient the denominator is the sum of all individuals of all species at the two sites and the numerator is the difference between populations at the two sites. The values of the coefficient range between 0 and 1. The Bray-Curtis dissimilarity was converted to a similarity measure by substracting the above coefficient from 1. This gives the compliment of the dissimilarity measure or the difference

between the dissimilarity value and the maximum value of 1. For example, if the dissimilarity between two data sets is 0.4 and the range of possible values is 0 to 1.0, then the similarity between the two sets must be 1.0-0.4 = 0.6. The closer the similarity coefficient is to 1.0 the more similar the two data sets.

Normal and inverse analyses were made of quantitative data. Normal analysis treats each sample as an entity and compares entities based on their combination of attributes (species). This allows an evaluation of population variations according to station which infers effect of the oil spill if other ecological conditions are similar. The inverse analysis treats each species as an entity and compares entities based on their relative abundance at stations of interest. This analysis was used to indicate species groups within certain habitats.

A weighted pair-group average clustering technique was applied to both types of analysis using a CLUSTR program from Davis (1973). This clustering strategy combined pairs of entities with the highest similarity coefficient and added entities to the group as a function of their similarity to the group. Results of the cluster analysis are presented as dendrograms. Further discussion of this numerical classification technique can be found in Clifford and Stephenson (1975).

RESULTS AND DISCUSSION

Sediment Samples

Substrate composition is recognized as an important abiotic variable which influences benthic community structure. Boesch (1973) identified three sediment-environment types in the Elizabeth River - Hampton Roads area which were characterized by different benthic community structures. Other researchers including Franz (1976) and Whitlatch (1977) have also found definite relationships between substrate types and species composition. Particle size analysis gives a very general classification of sediment type, but for our purposes this was sufficient.

Results are presented in Figures 3 through 6. The triangular co-ordinate graphs do not include the gravel fraction, but it was greater than 5% of the total at only two stations (B3 and B-4). Fine sand was the dominant particle size (0.42 - 0.063 mm) in the samples. There was less coarse sand and very little silt and clay or gravel. Notable exceptions were Stations I1, which had 64% silt and clay, and B4, which had 39% gravel. Most of the stations had similar substrates, and by this rather rudimentary sediment analysis one might not expect great variations in benthic populations as a result of substrate composition.

Invertebrate Samples

A total of 86 different taxa were identified from 40 samples.

The majority of organisms were polychaete worms, bivalve molluscs, and amphipod crustaceans. The polychaetes *Nereis sp.*, *Heteromastus filiformis*, and *Scolecolepides virides* were the most common and widespread throughout the study area. The bivalves *Gemma gemma* and *Tellina sp.* were also common and widespread. Among the amphipods *Gammarus sp.* and *Monoculodes edwardsi* were the most common.

The internal marsh stations had the highest population densities with 26 taxa and 2,013 individuals counted at Station B1 and 15 taxa and 2,813 individuals counted at Station D1. The lowest densities were noted at stations J4 (10 taxa: 25 individuals), F1 (4 taxa: 32 individuals) and, G3 (9 taxa: 19 individuals). In general, populations at the western shore stations appeared higher than those from the eastern shore.

The results of normal analysis are presented as dendrograms in Figures 7 through 11. The intertidal stations formed two major clusters: tidal creek stations and fringing marsh stations. Both tidal creek stations (E1 and G1) had low diversity and density. The reason for such low numbers at G1 may have been oil, which was found on the marsh substrate in 1976 and 1977. The control station at E1, however, had lower numbers than the oiled station and without a healthy or densely populated control the influence of oil on the benthic community at G1 cannot be evaluated with confidence. The problem at E1 probably was site selection. (Personal communication with Dr. Dauer at Old Dominion University, who has done extensive sampling of benthos in the area of E1 and has found high density populations.) The particular area of the mouth of Old Plantation Creek which we sampled may have been subject to severe scouring during ebb tides and this type of habitat would normally have low population densities.

The second group of intertidal stations was composed of the fringing marsh stations. There were two subgroups within this category. The control stations (D1 and I1) had the highest degree of similarity, then the lightly affected western shore marsh station (B1) joined the cluster. The last station to join was the more severely affected eastern shore marsh at Poles Bluff (J1). The western shore marsh appears to have recovered more fully than did the eastern shore marsh and this is probably a result of the different degree of oiling at the two sites. Station J1 had a moderate species similarity with the other stations but the population density was much lower. This condition, which appears to be a result of the oil spill, will be discussed further under the inverse analysis.

The stations sampled at the three foot depth formed three clusters with another station not grouped at all. In the first cluster the control and oiled stations from the western shore (C1 and A1) grouped before joining the cluster of eastern shore control and oiled stations (I2 and 4 and H1). (During the sorting of samples from transect I, the organisms from I2 were accidentally mixed with those from I4. The notation I2&4 reflects this combination of communities from both depths.) It appears that the influence of the oil spill was not as great a factor as the geographical location of the stations. The benthic

community is composed of populations of burrowing forms typically found in the sandy bottoms common to all four stations.

The second cluster of stations (J2, D2, and G2) did not group according to the presence or absence of oil. Their benthic communities were composed of animals typical of the eelgrass beds at these stations. The presence of barnacles, isopods, and amphipods found on eelgrass sets these stations apart but there is no evidence that the oil spill had influenced the population structures.

Stations E2 and F1 south of the Town of Cape Charles grouped separately from the others. This appears to be related to natural factors rather than the oil spill as both stations were in unaffected areas. The sparse populations at these sites are related to the less hospitable shifting sand substrate associated with their proximity to the mouth of the Bay (personal communication with D. F. Boesch, Virginia Institute of Marine Science).

Station B2 was not similar to any of the others at this depth. The species diversity was very low and the dominant organisms were two species commonly found at many stations in the study at other depths.

The stations at the five foot depth formed two distinct clusters and four less distinct groups (Figure 9). Stations J3, I3, F2, and E3 cluster according to common species. The diversities and densities are low and the communities are similar at all four sites, with sand-burrowing organisms dominant. There did not appear to be any noticeable influence of the oil on the benthos. Stations G4 and H3 were located beyond a protective sandbar, and their benthic populations were characterized by the haustorid amphipods found commonly in deeper sandy habitats.

There were six other stations collected at this depth. No definite pattern can be seen in the clustering of these stations which would identify the presence of oil as a determining factor. There was a natural depression in the bottom at Station G3. There was a noticeable oil sheen on the samples collected at this station. The invertebrate community at this station was poor in diversity and density, but without a comparable control environment the effect of the oil is not proved.

Stations D3 and C2 were in eelgrass communities. They did not cluster together, but visual examination of the data showed they had some of the eelgrass epifauna in common.

The stations collected at the ten foot depth were arranged in four distinct clusters, none showed effects of the oil. The pattern appears to be an association according to geographical location or population, with western shore stations grouping with the northern-eastern shore site and the southern-eastern shore sites grouping separately.

Figure 11 depicts the similarity relationships between all stations. There were two western shore clusters (A & B), one made up of sand beach transects and the other containing the subtidal stations of the marsh transects. There were two large clusters of eastern shore stations. One includes creek mouths and the oiled marsh intertidal site J1. These stations cluster because they all had sparse populations (C). The subtidal stations with moderate populations formed the other cluster of eastern shore sites (D). The high population intertidal stations cluster separately (E). Based on the results of normal analysis, the similarities of invertebrate communities are arranged according to geographical and population factors which cannot be related to the oil spill with the possible exception of station J1.

The results of the inverse analysis are presented as dendrograms in Figure 12 through 16. The intertidal organisms clustered into six groups. Three of these clusters (A, D, & E) were composed of rare species which were found at one or two stations only. There were two other clusters of more common species (B & C), but their distribution did not appear to be limited by the presence of oil.

The sixth cluster of intertidal species (F) is one which may give evidence of the effect of the oil spill. This cluster is composed of three species: the polychaete worm *Nereis*, the amphipod *Gammarus*, and the oligochaete worm *Marionina*. These three organisms were found at more stations and in higher densities than any other intertidal species. The oligochaete *Marionina* was found in high numbers at the oiled station J1, low numbers at the control station I1, and about the same density at the western shore station D1 and B1. The polychaete *Nereis* was found in higher numbers at the moderately oiled marsh B1 than at the control marsh D1. It showed comparable populations at the creek mouth stations E1 and G1, but it was higher at the control marsh I1 than at the heavily oiled site J1. *Gammarus*, which is the most sensitive to oil pollution of the three organisms in this cluster, was found in low numbers at both oiled marsh sites B1 and J1 and higher numbers at both control marshes D1 and I1. For *Gammarus* particularly, and the others to a lesser degree, there is evidence that populations were lower at the oiled stations than at the controls. Station J1 at the Poles Bluff marsh appeared to be the most severely affected, as both *Nereis* and *Gammarus* populations were depressed in comparison to controls.

Inverse analysis of the population data for the three subtidal depths yielded species groups that do not show effects of the oil spill (Figures 13-15). The populations cluster according to the rarity of organisms or the substrate present (most noticeably the eelgrass communities).

At the three foot depth there were two major clusters (Figure 13). One was a large group of organisms which occurred at only one or two stations (A) and the second was a smaller cluster of common species (B).

The bivalve mollusc *Gemma gemma* was the most abundant species, with the barnacle *Balanus*, the polychaete worm *Scolecolepides*, and the amphipod *Monoculodes* also well represented. A comparison of occurrences at oiled versus control sites did not indicate preference by a group of species for one over the other.

The species groups identified at the five foot depth fell into four clusters (Figure 14). Two clusters of rare or uncommon species can be identified (A & B), neither of which indicates influence of the oil spill. There were also two clusters of common species: an eelgrass epifaunal community (D) and a sandy bottom infauna community (C). The clam *Gemma gemma* was again the most abundant species. Other common organisms were the barnacle *Balanus*, the ribbed mussel *Geukensia (=Modiolus)*, the amphipod *Acanthohaustorius*, and the clam *Mulinia*.

There were three major clusters of species at the ten foot depth (Figure 15). Two of the clusters were of rare species which were found at either the southern-eastern shore stations (C) or the western shore and northern-eastern shore sites (A). This again points out the possibility that the area south of Cape Charles is in a zone of higher salinity than the other areas in this study. The common species made up the third major cluster, with *Gemma gemma* still the most abundant organism (B). The polychaetes *Spiophanes bombyx*, *Streblospio benedicti*, and *Glycera* and the amphipod *Phoxocephalus* were also common at this depth throughout the study area.

Figure 16 shows the similarity between all species collected in the study. There are four major clusters in this dendrogram: the common and widespread forms (A), rare species found throughout the study area (B & D), and species found commonly at the deeper water stations (C). These clusters do not indicate that the oil spill influenced population densities as there was no definite preference for control over oiled sites.

CONCLUSIONS

There are certain limitations in this study which must be considered before conclusions may be drawn from the results. The most important factor is the status of the control stations. It is very difficult to assign control status to an estuarine transect and compare data with an affected transect because of the many variables which come into play. Predictable associations of species occur in natural habitats, and the species composition of these associations will change according to variations in natural environmental conditions such as temperature, salinity, substrate, and the season. These variables affect the population size of the species in association and, therefore, will have some determining influence on the overall composition of the benthic community.

Others involved in the evaluation of oil spill effects have had difficulty in assigning control status to nearby environmentally similar sites because of slight variations in salinity or sediment types

(Michael et. al., 1975). In the present study the control transects E and F on the eastern shore may have been in the Bay Mouth salinity zone rather than the Polyhaline zone in which the other transects were located. Increased water currents, coarser sand, and less silt could be affecting the distribution of invertebrates. These factors may be responsible for the lowered populations found at these transects (Payne, 1977). For these reasons the choice of transects E and F as controls may not have been as sound as one would hope, but with so much of the eastern shoreline of the Bay coated with oil these areas were about all that were left to work with.

Another factor to consider in interpreting the results is the population dynamics of the estuarine benthos. The oil spill occurred in February when the population levels were low. This meant that fewer organisms would have been killed than if the spill had occurred in early summer when the populations peak. The active larval recruitment and the reproduction of organisms, which occurred between the spill in February and when the samples were collected in April and June, would have allowed time for the less severely affected stations to recover. This appears to be what happened at stations B1, where a light to moderate amount of oil came ashore but the invertebrate populations were similar to the control site at D1. The heavily oiled station at J1 did not recover as quickly, however.

The characteristics of the oil and the effected environment also helped to reduce the impact of the spill. The #6 oil involved was lower in the toxic naphthalene compounds than lighter fuel oils would be and, perhaps because of the low water temperatures, it floated on the surface rather than mixing readily with the water column. These factors helped reduce the aquatic toxicity of the spill. The particle size analysis indicated that the bottom sediments of the affected area were sandy rather than highly organic. This was also fortuitous because the oil did not incorporate into the sandy materials as strongly as it would have in muddy substrates.

Taking these factors into consideration, one may now draw some generalizations. The data agree with conclusions made by Hershner and Moore (1976), who studied effects of this oil spill on marsh grass and larger mollusc populations, that impacted areas appear to have recovered or are recovering. Comparisons between oiled and control sites gave generally encouraging results. The subtidal areas do not appear to have been affected by the oil spill, and only one of the intertidal areas exhibited possible signs of degradation. The shoreline invertebrate populations appeared to have escaped any catastrophic damage as a result of the February 1976 oil spill.

ACKNOWLEDGEMENTS

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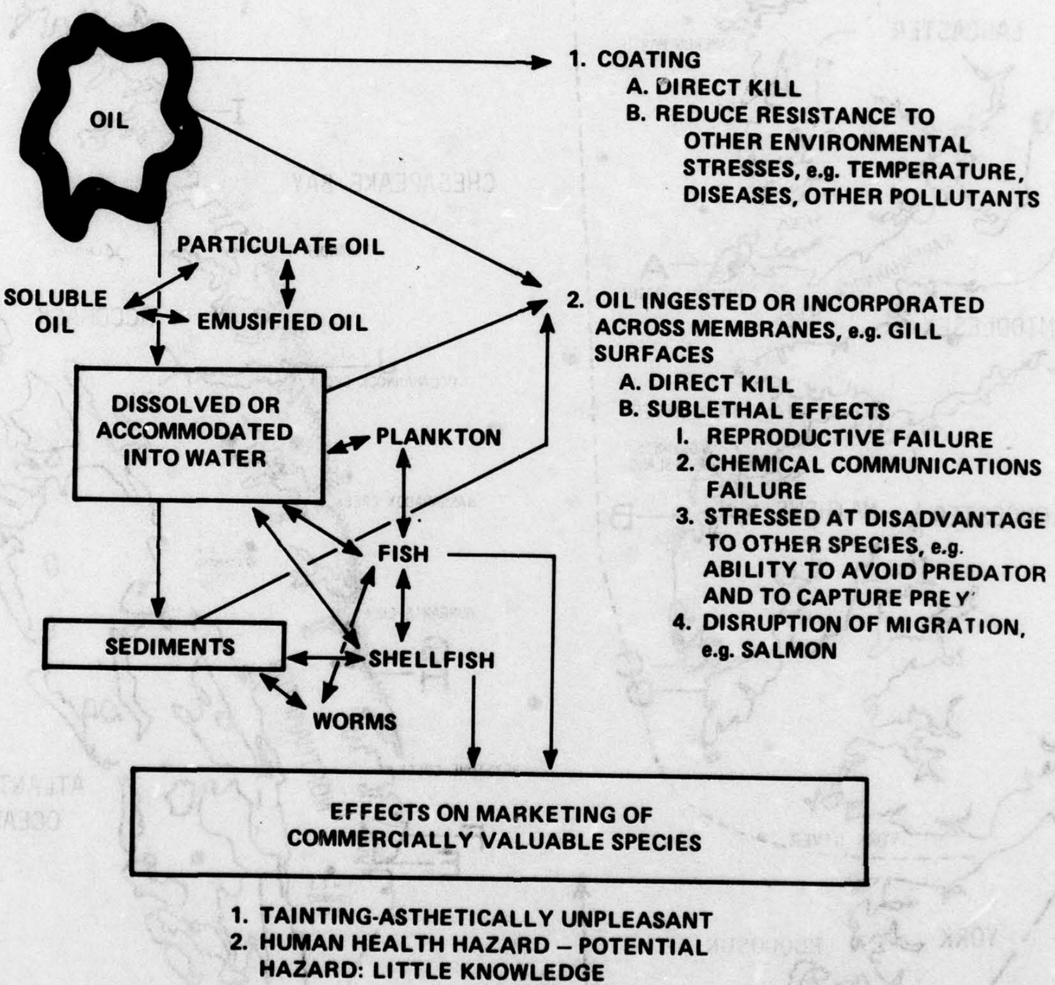
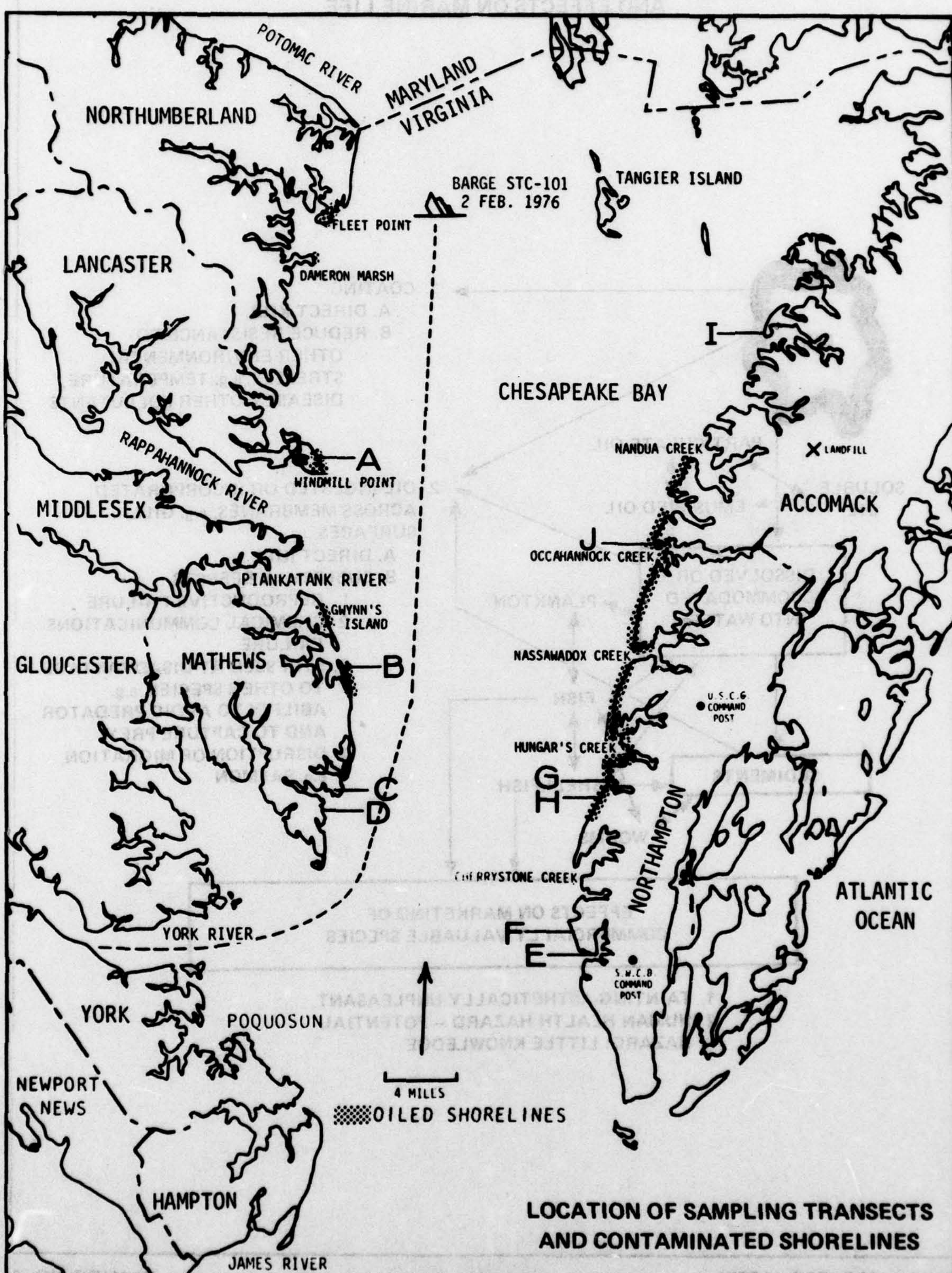
PATHWAYS OF OIL INCORPORATION INTO MARINE LIFE AND EFFECTS ON MARINE LIFE



Source: U.S. EPA (1975)

FIGURE NO. 1

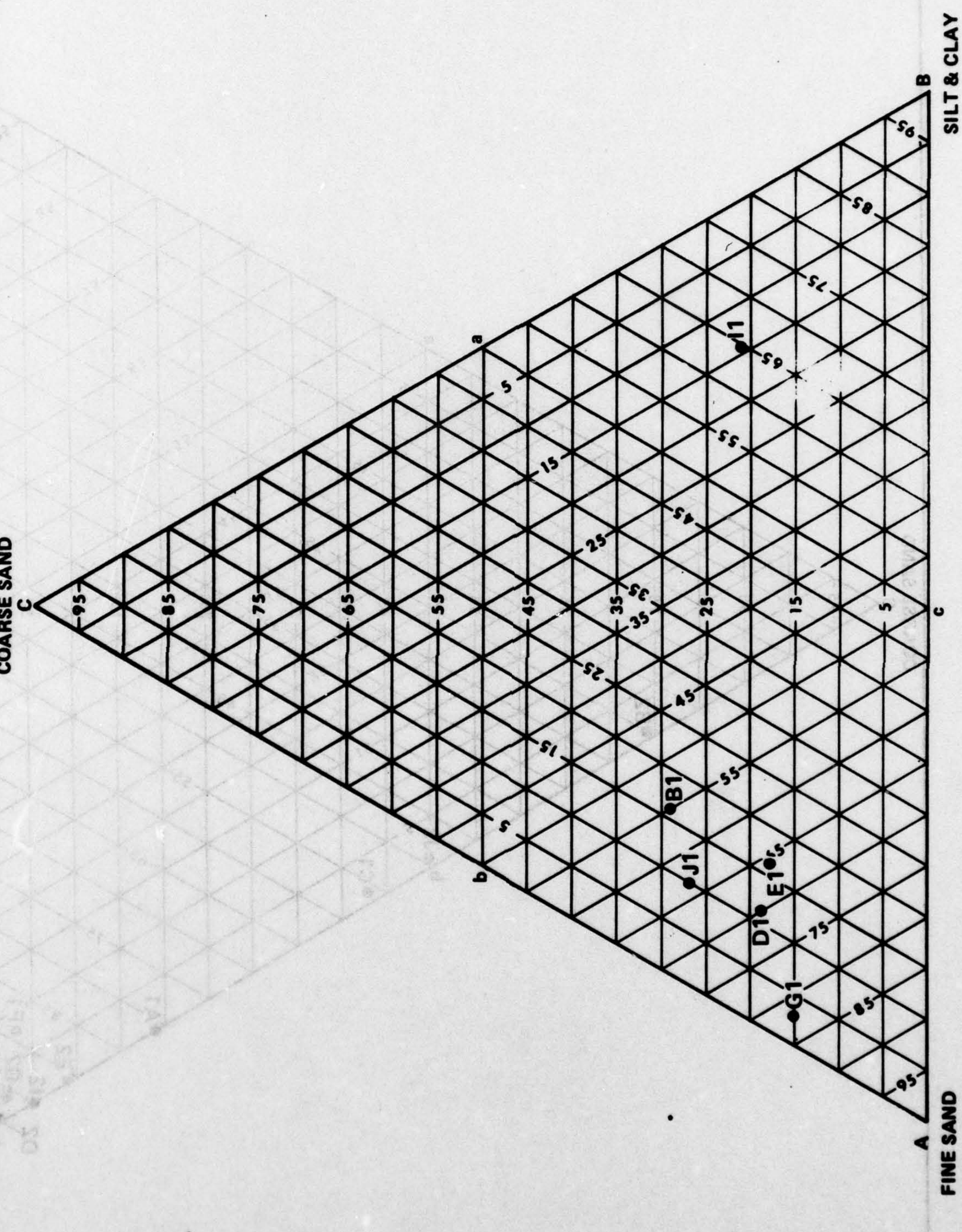


LOCATION OF SAMPLING TRANSECTS AND CONTAMINATED SHORELINES

Source: State Water Control Board – B.S.F.S.

FIGURE NO. 2

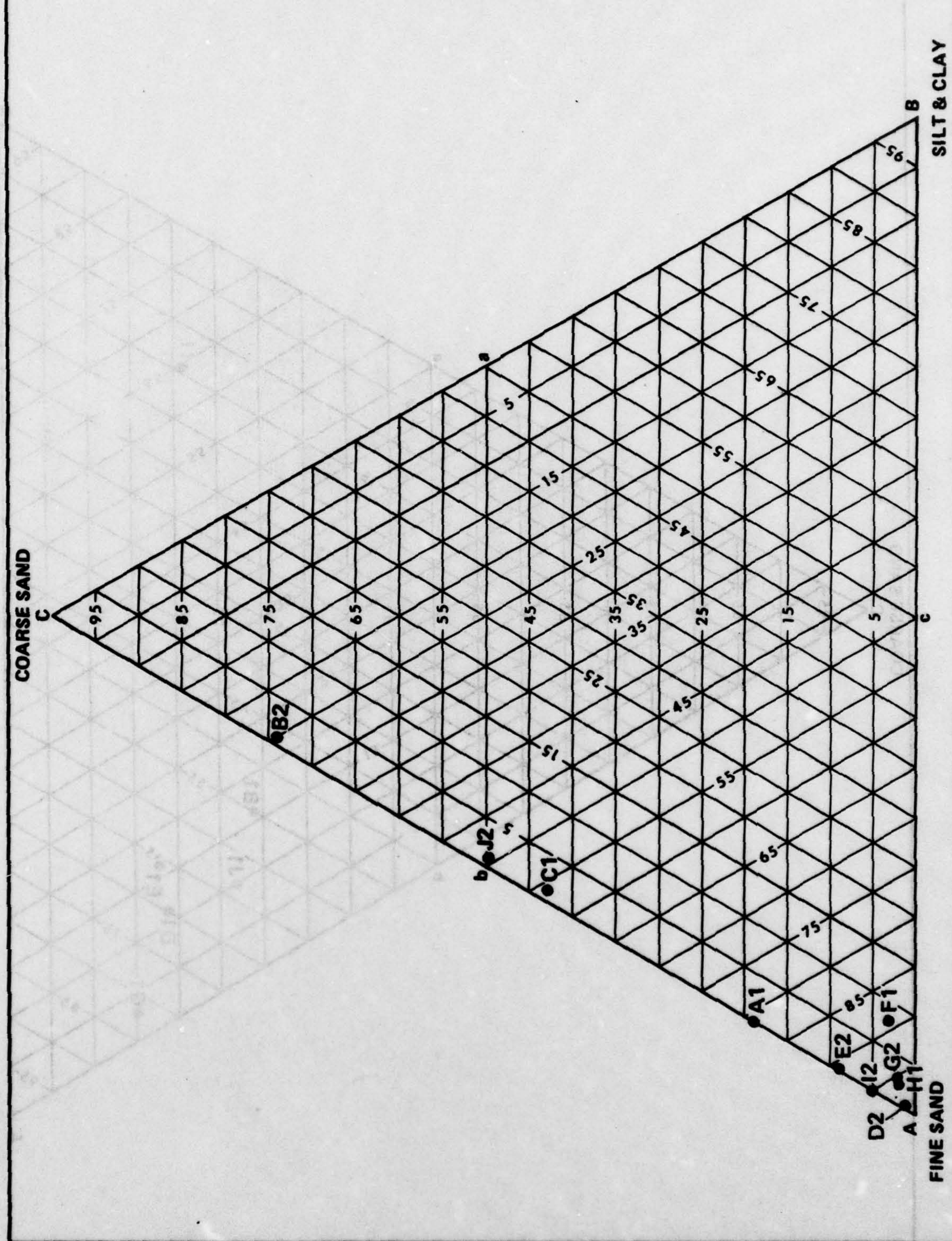
PARTICLE SIZE DISTRIBUTION OF INTERTIDAL STATIONS



Source: State Water Control Board – DES

FIGURE NO. 3

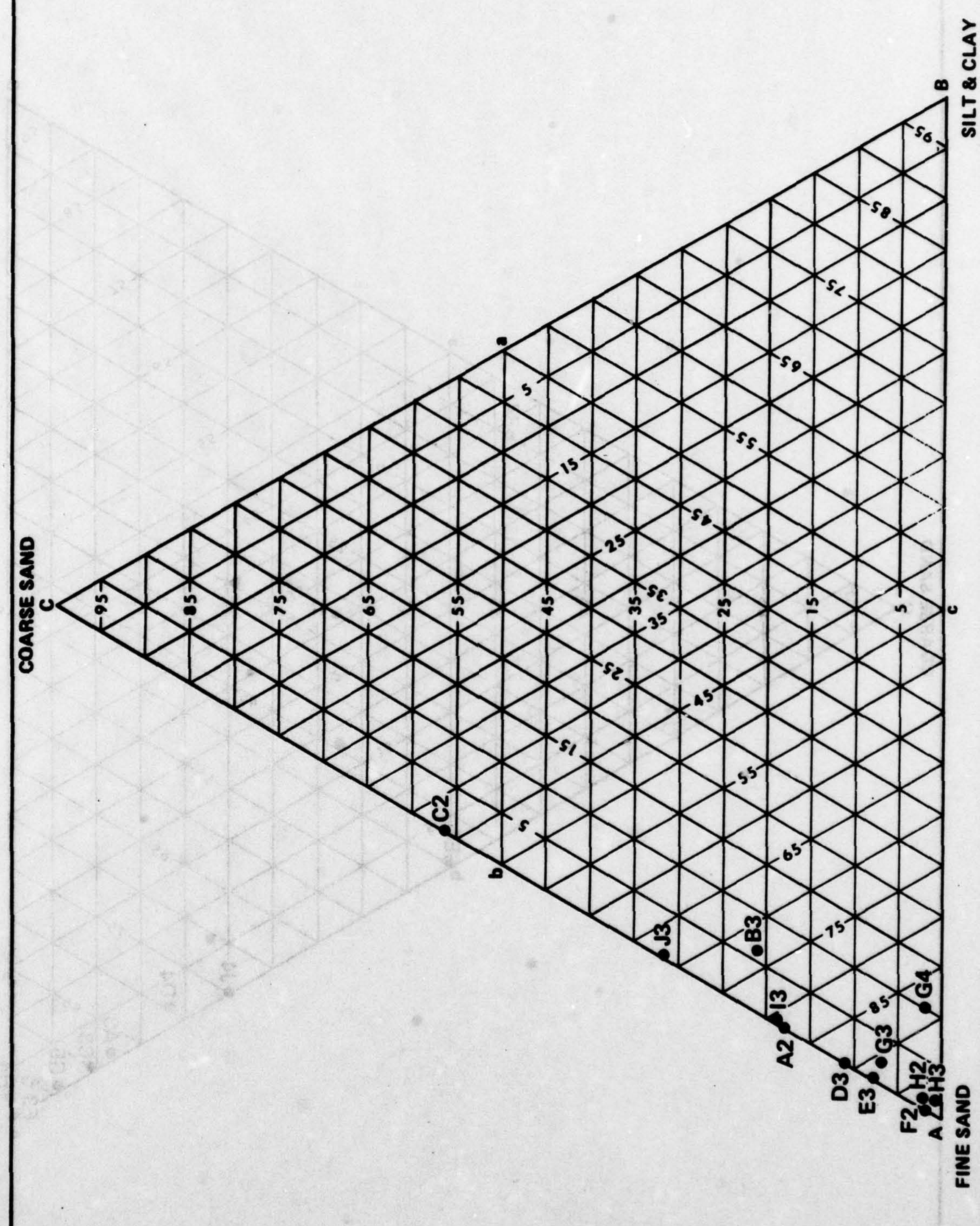
PARTICLE SIZE DISTRIBUTION OF 3' DEPTH STATIONS



Source: State Water Control Board – DES

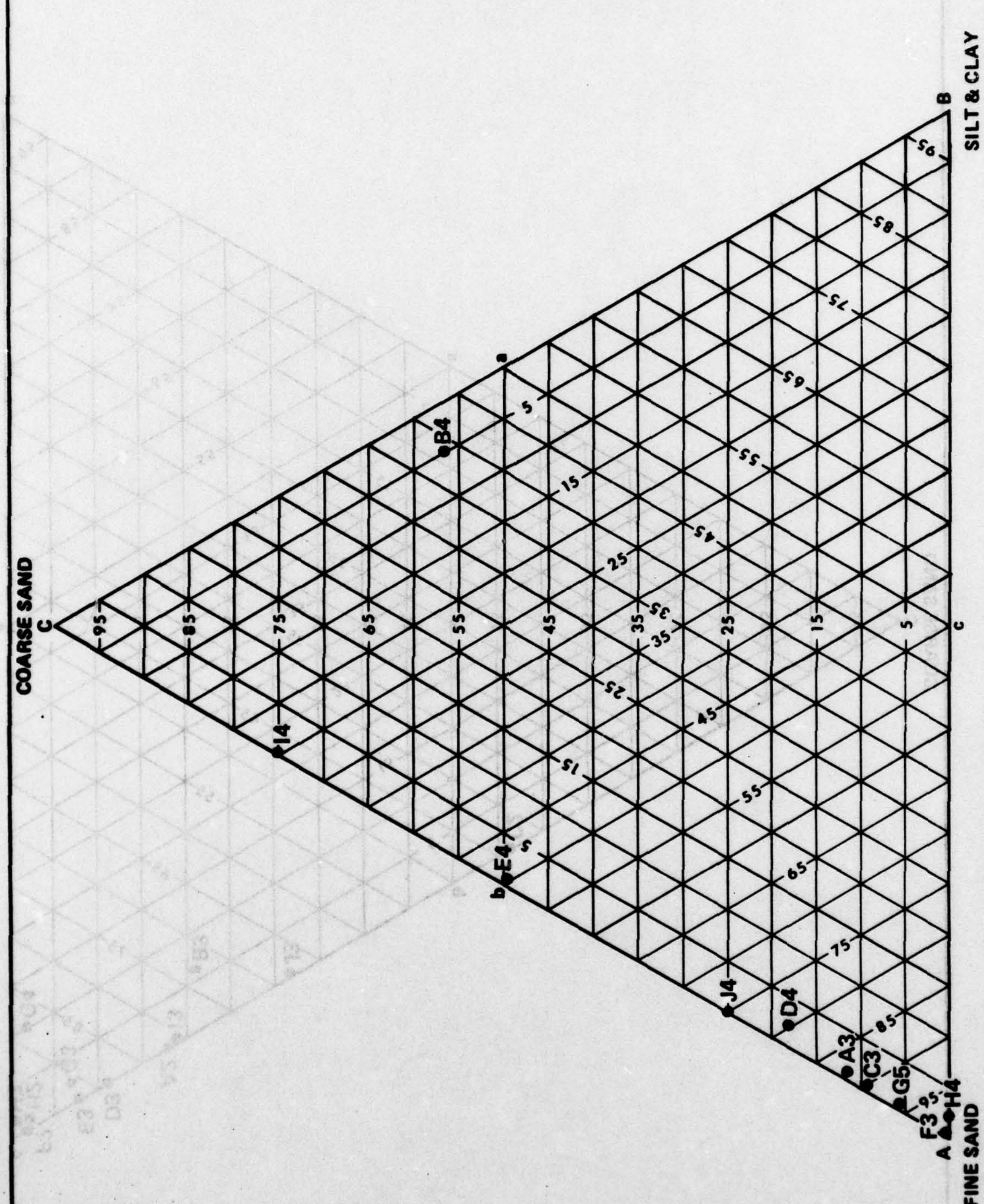
FIGURE NO. 4

PARTICLE SIZE DISTRIBUTION OF 5' DEPTH STATIONS



Source: State Water Control Board – DES **FIGURE NO. 5**

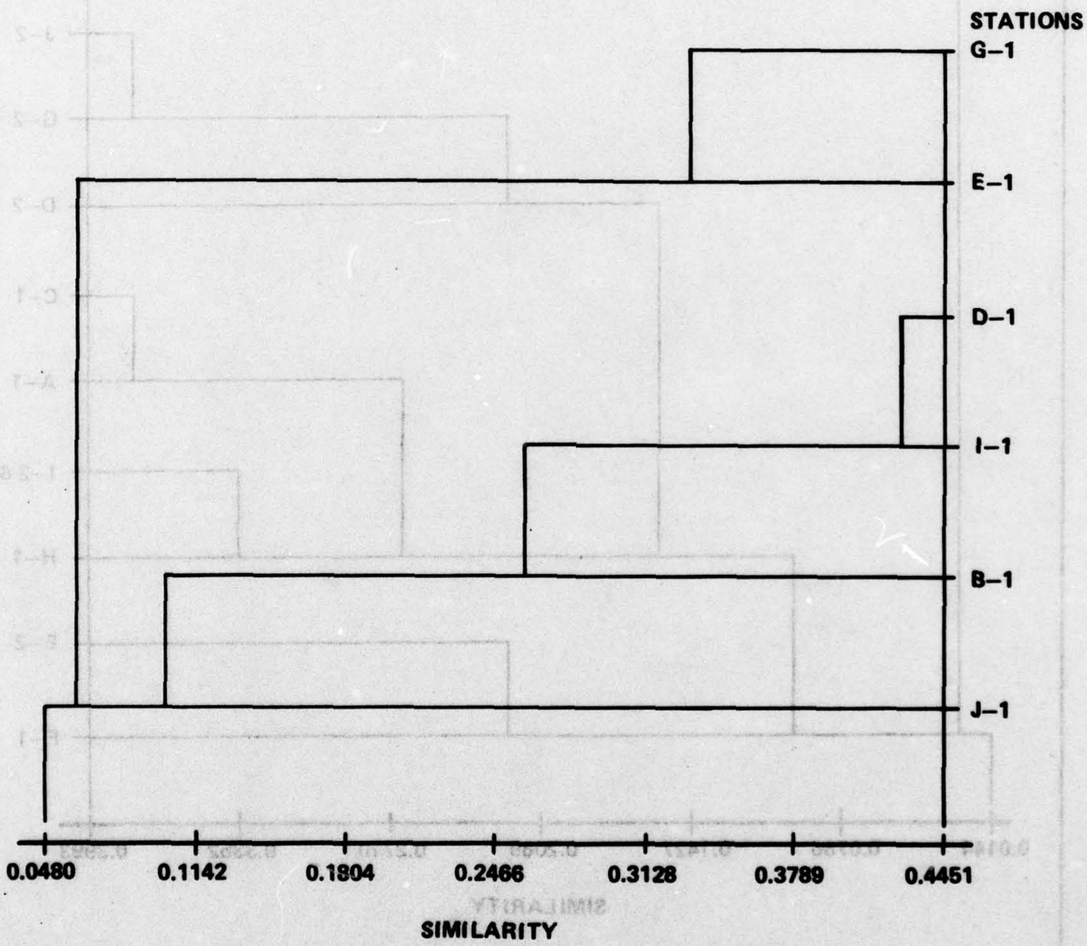
PARTICLE SIZE DISTRIBUTION OF 10' DEPTH STATIONS



Source: State Water Control Board — DES

FIGURE NO. 6

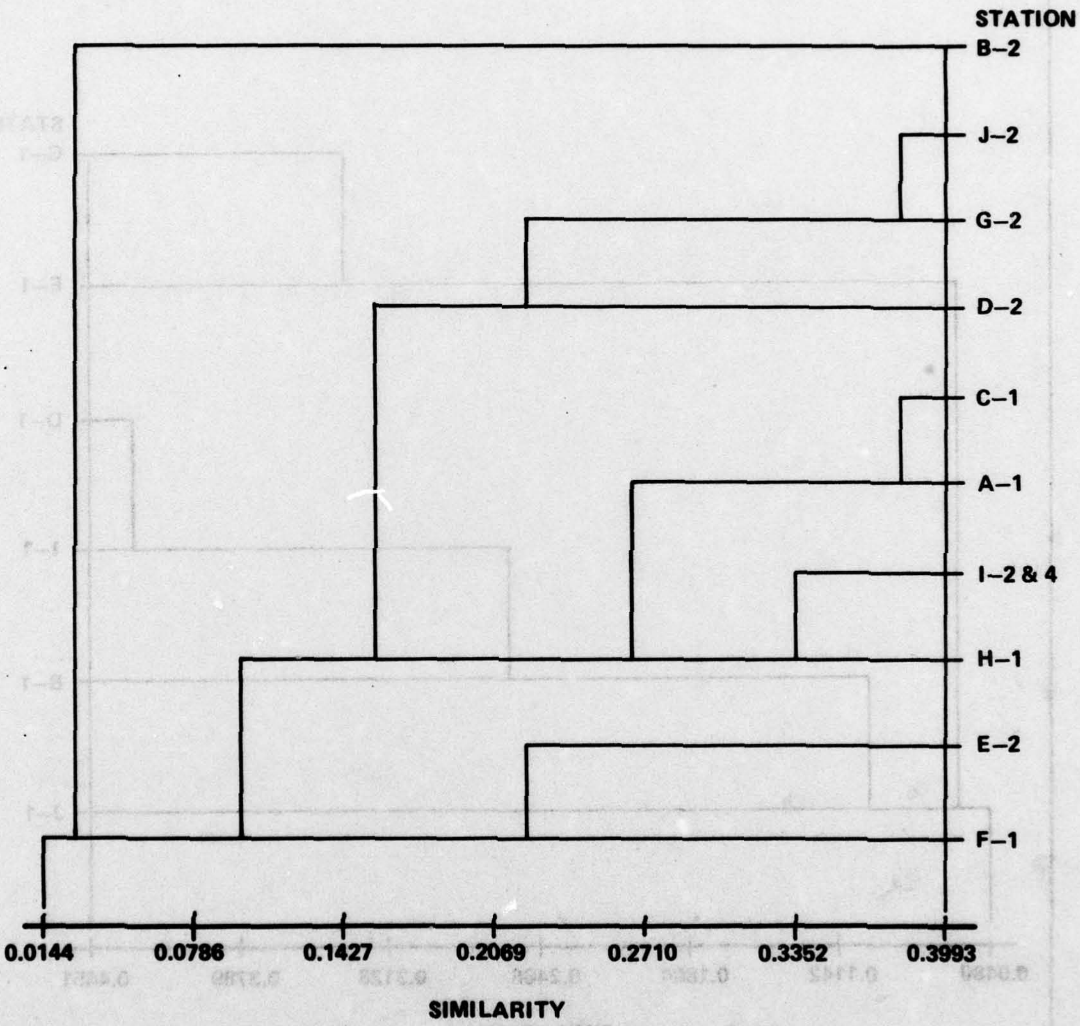
NORMAL ANALYSIS OF INTERTIDAL STATIONS



Source: State Water Control Board – DES

FIGURE NO. 7

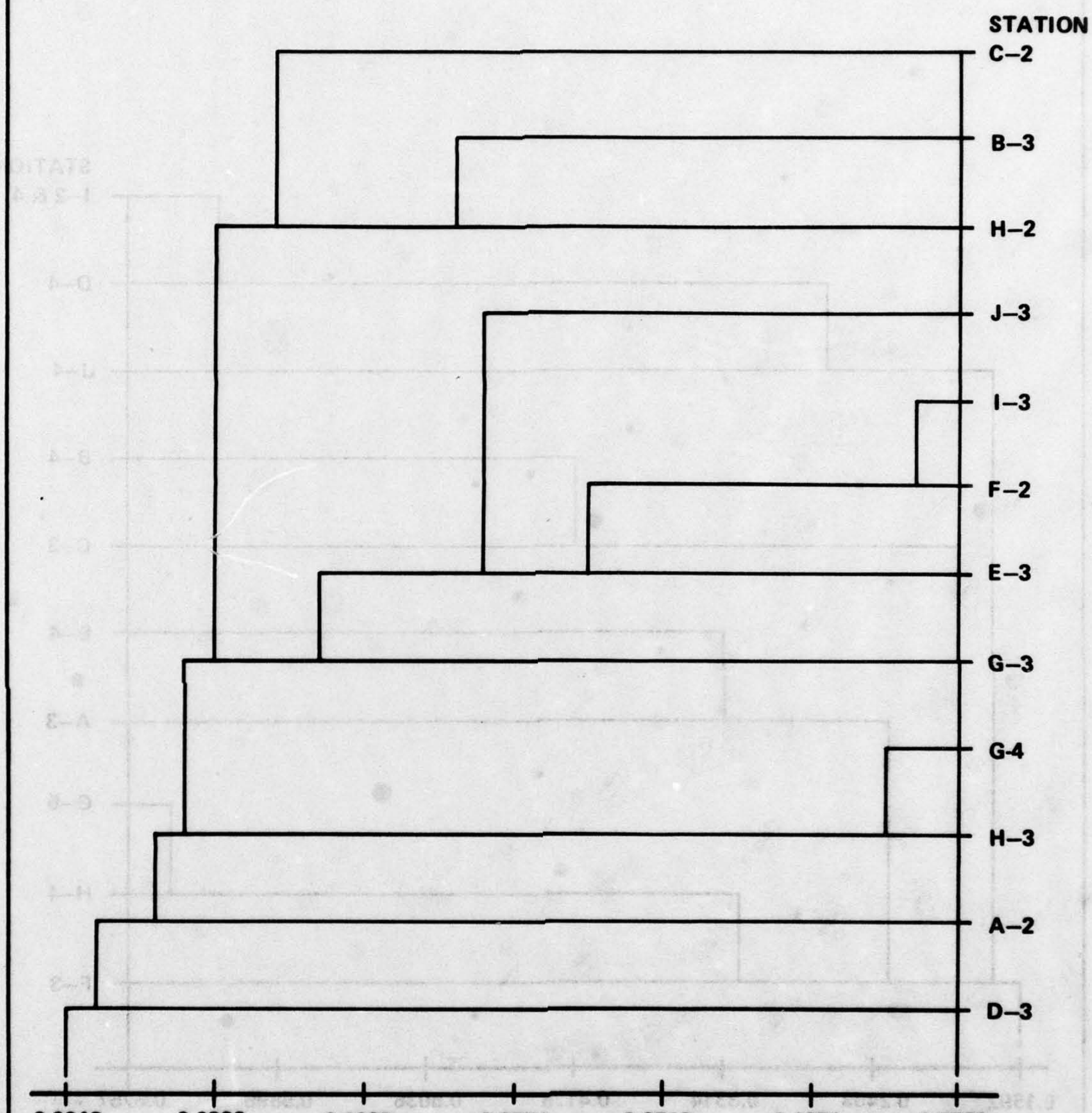
NORMAL ANALYSIS OF 3' DEPTH STATIONS



Source: State Water Control Board – DES

FIGURE NO. 8

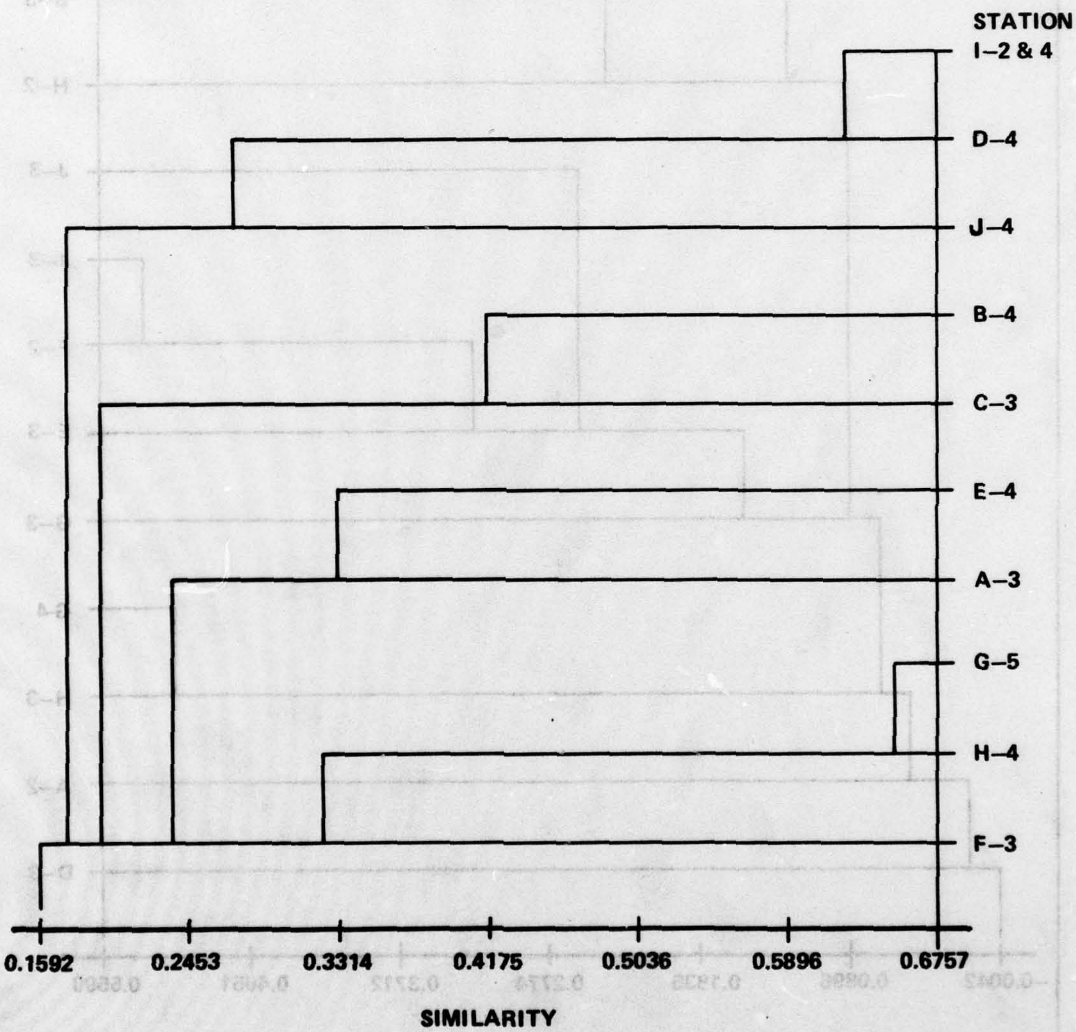
NORMAL ANALYSIS OF 5' DEPTH STATIONS



Source: State Water Control Board – DES

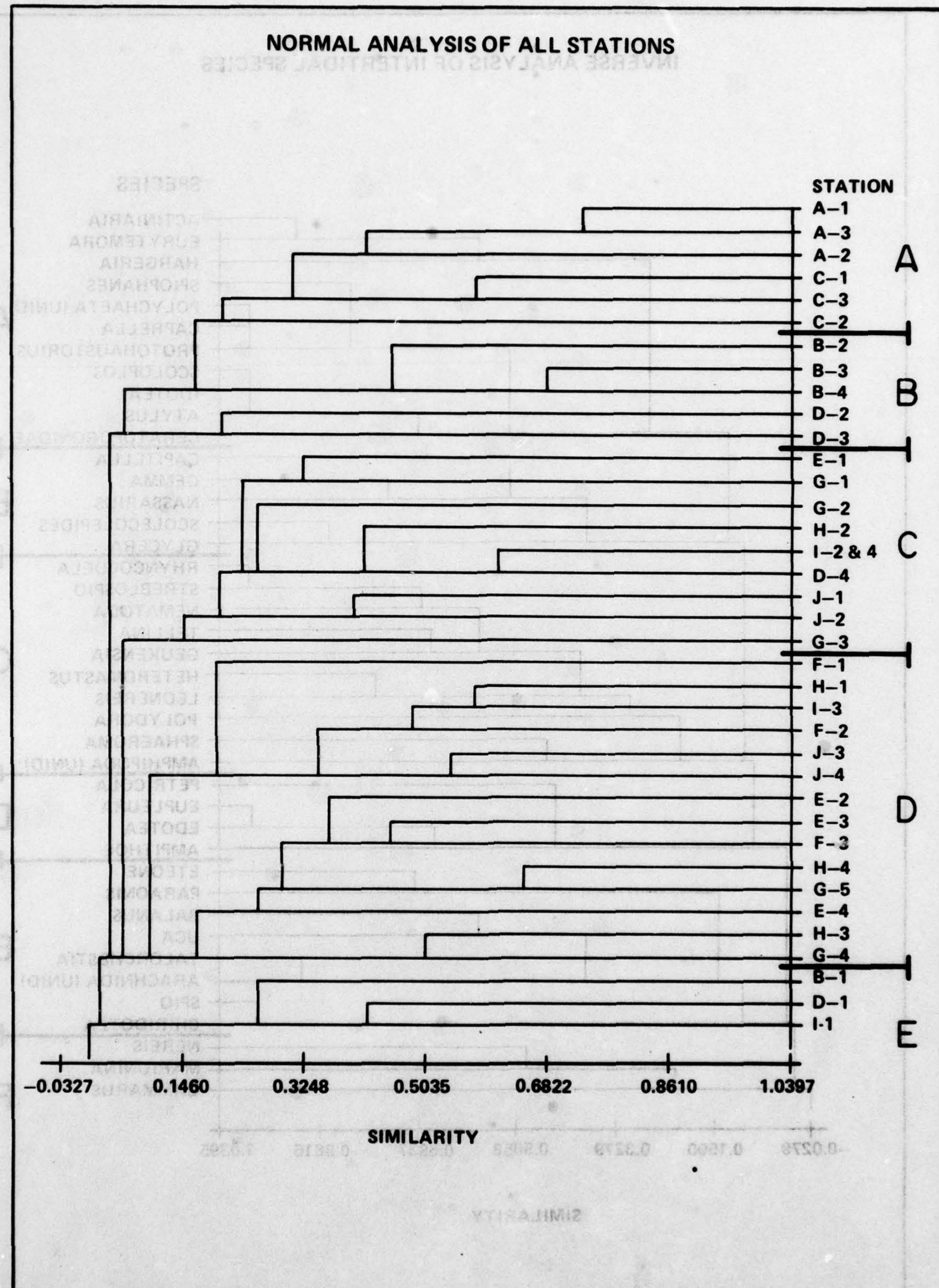
FIGURE NO. 9

NORMAL ANALYSIS OF 10' DEPTH STATIONS



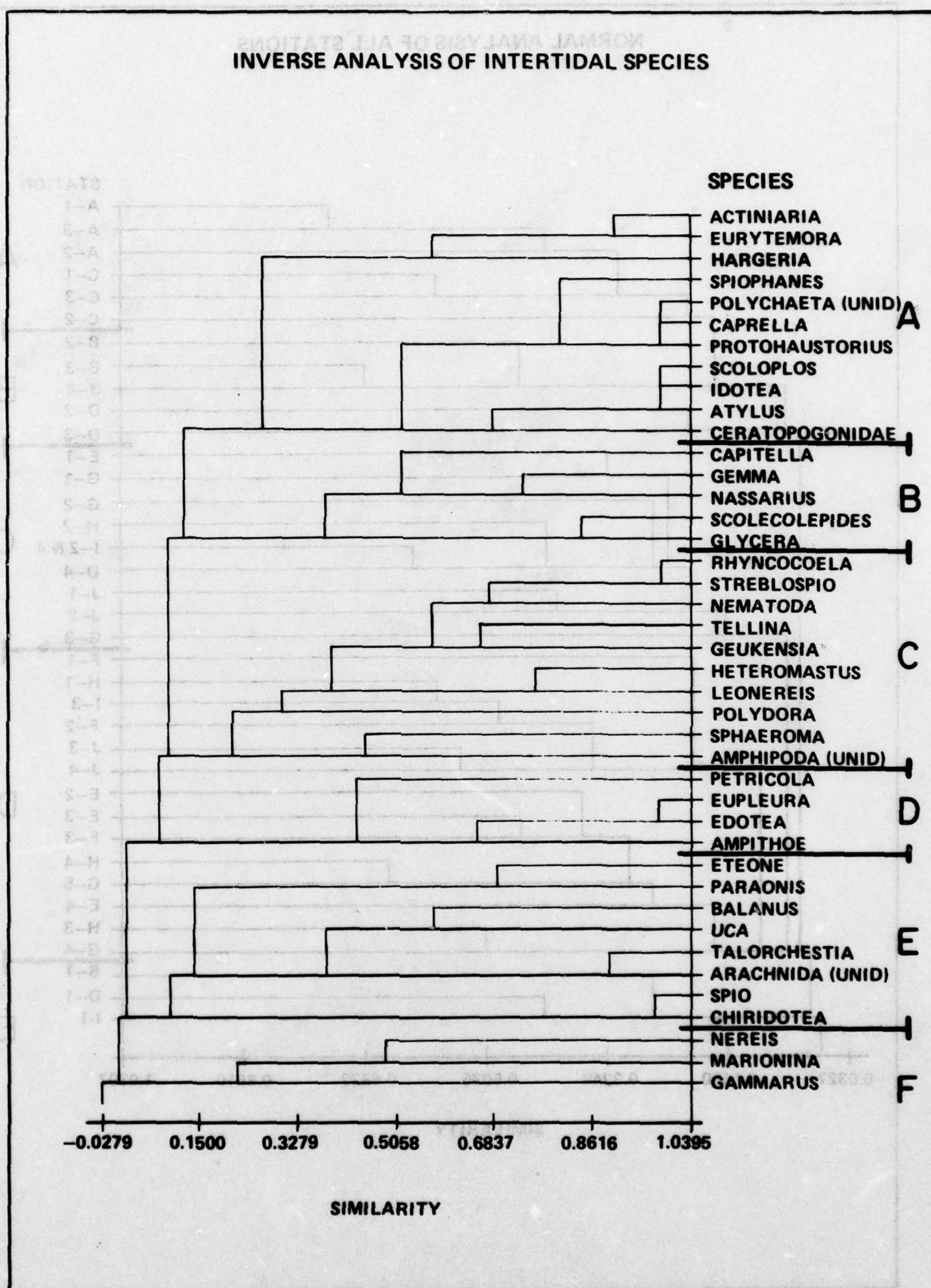
Source: State Water Control Board -- DES

FIGURE NO. 10



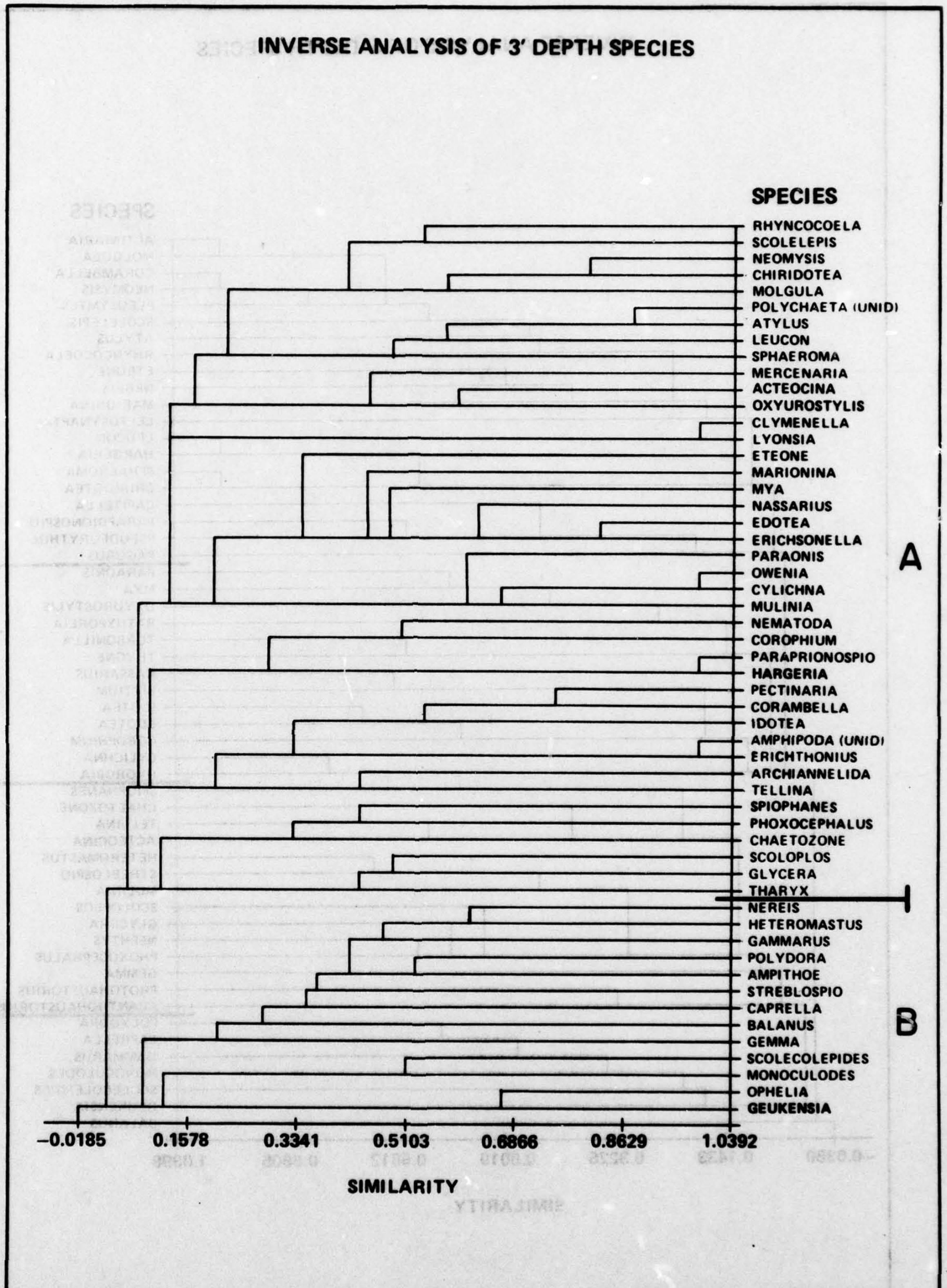
Source: State Water Control Board – DES

FIGURE NO. 11



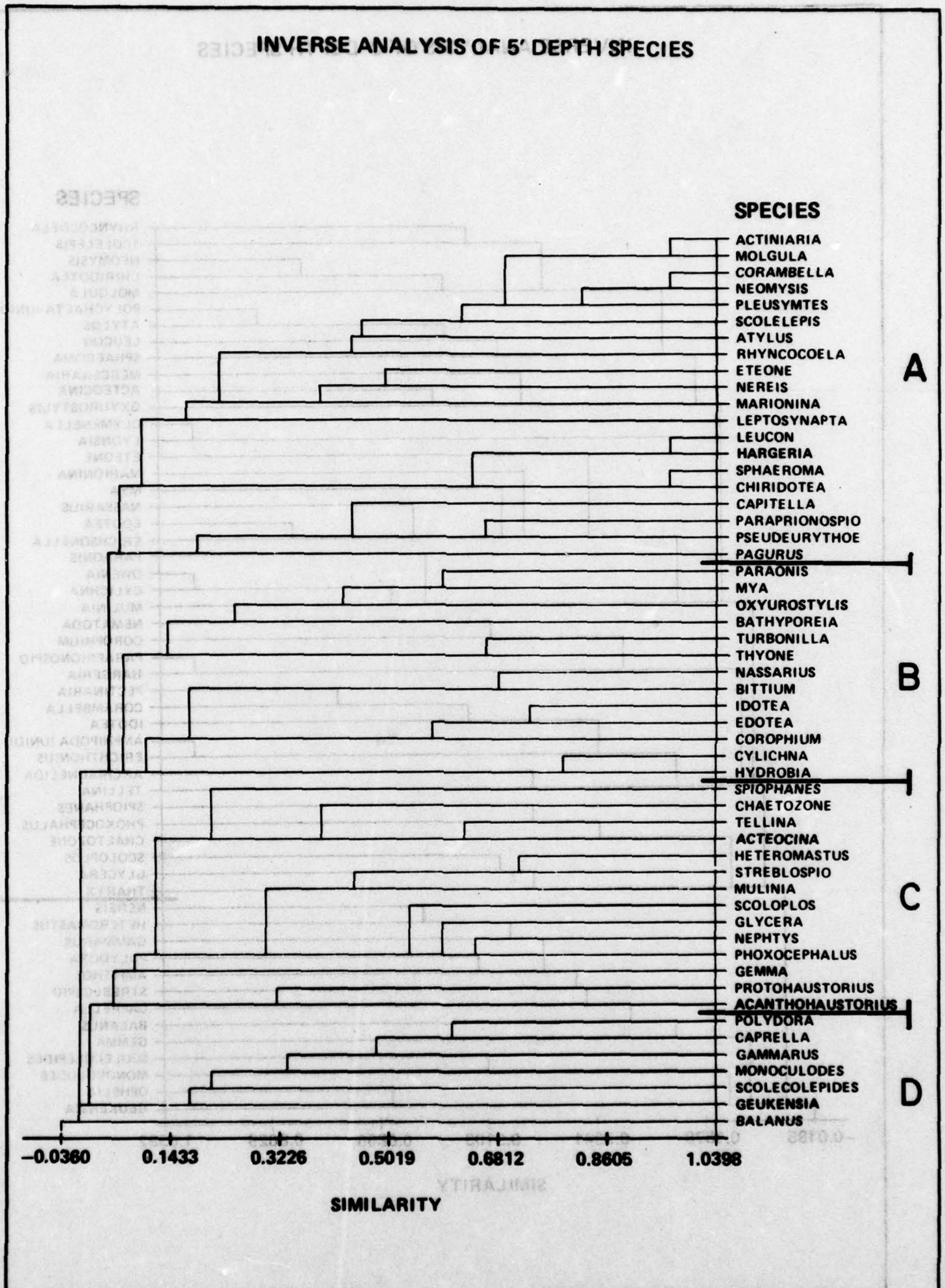
Source: State Water Control Board – DES

FIGURE NO. 12



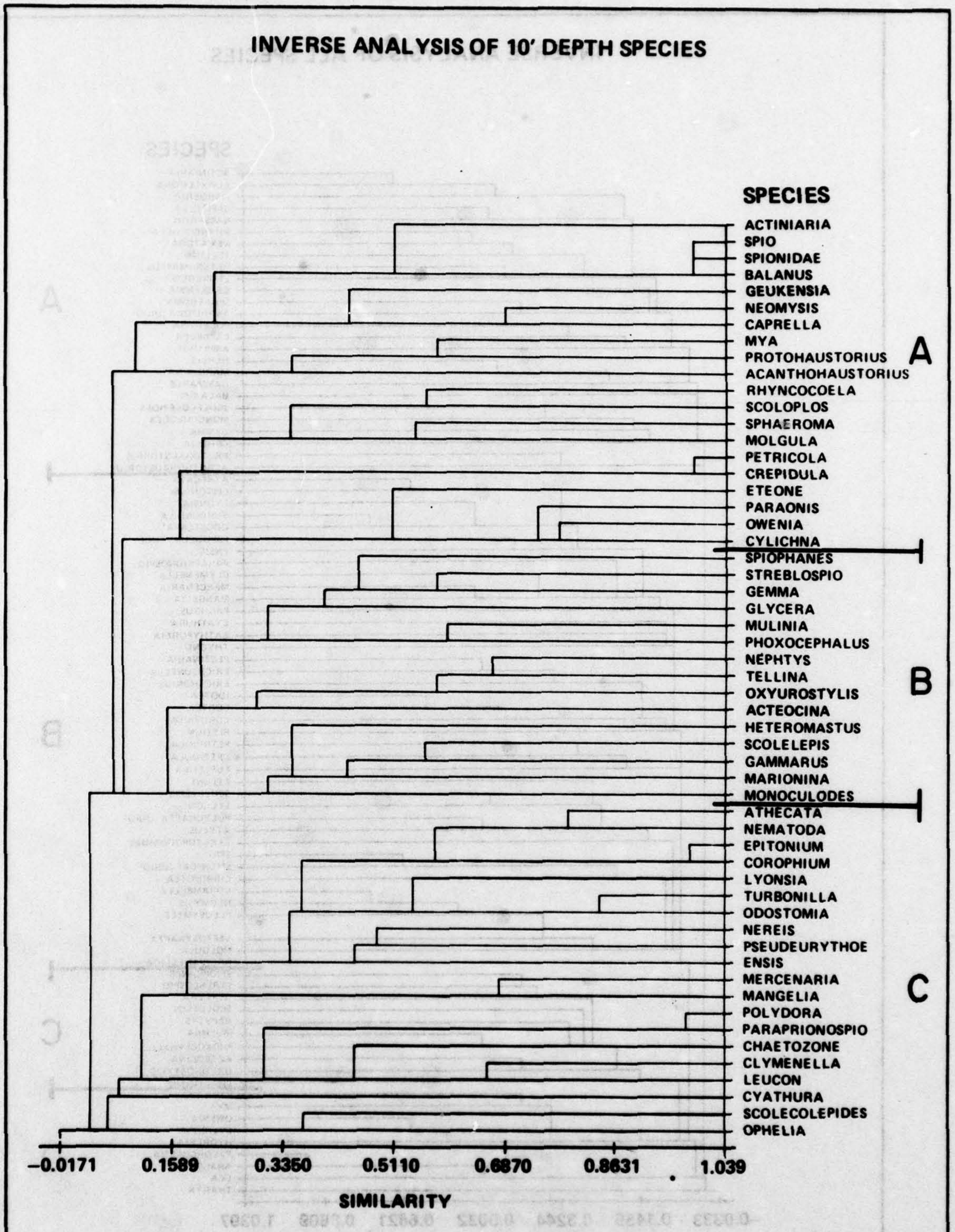
Source: State Water Control Board – DES

FIGURE NO. 13



Source: State Water Control Board – DES

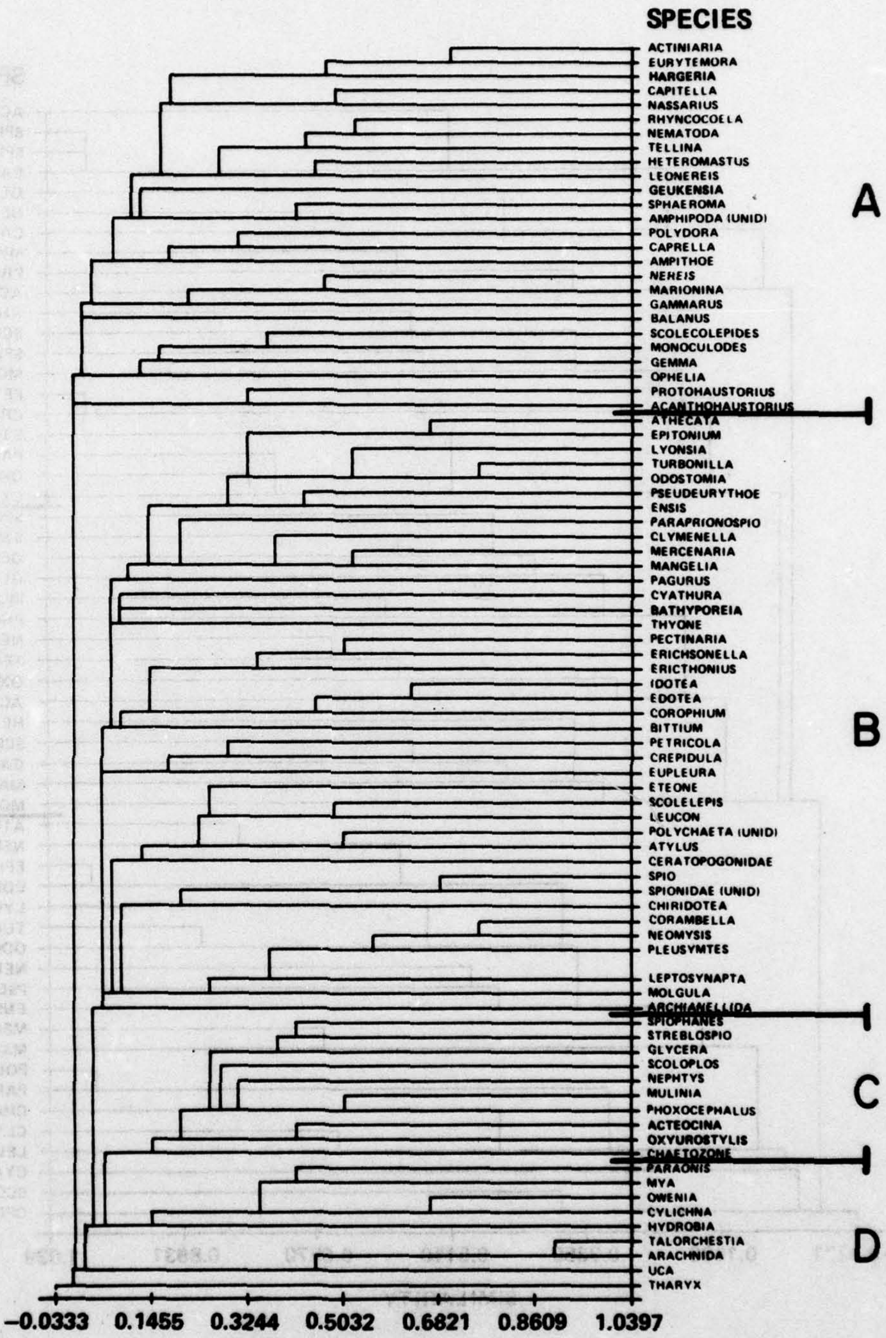
FIGURE NO. 14



Source: State Water Control Board – DES

FIGURE NO. 15

INVERSE ANALYSIS OF ALL SPECIES



Source: State Water Control Board – DES

FIGURE NO. 16

THE URQUIOLA OIL SPILL (5/12/76): OBSERVATIONS OF BIOLOGICAL DAMAGE ALONG THE SPANISH COAST

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ABSTRACT

On 12 May 1976, the supertanker Urquiola ran aground, spilling nearly 30,000 tons of Persian Gulf crude along 215 km of Spanish coastline. Quadrat analyses of a sandy tidal flat, a salt marsh, and a mud flat indicated that *Cerastoderma edule*, the edible cockle, and the marsh gastropod, *Littorina littorea*, were the macrobenthic faunal residents most vulnerable to the effects of the spilled oil. Other species of bivalves (*Scrobicularia plana*, *Tellina tenuis*, *Venerupus decussata*) suffered lower mortalities ranging from 19-30%. Sub-lethal damage to cockles, small intertidal schooling fish, limpets and nudibranchs was also observed.

It was difficult to assess the effects of oil on annelid and decapod crustacean populations. However, surviving individuals exhibited no indications of sublethal impairment of locomotion or of escape responses.

Some species of macrobenthic fauna are obviously more sensitive than others to the deleterious effects of spilled oil. Physiological differences may account for this fact. However, it is suggested that habitat preferences may also strongly influence species mortality.

INTRODUCTION

On May 12, 1976, during a spring low tide, the supertanker Urquiola ran aground and exploded at the entrance to La Coruña harbor in northwest Spain (Fig. 1). Of the 107,000 tons of Persian Gulf crude on board, only 10,000 tons were later removed. Although most of the oil burned after the explosion, an estimated 25,000 tons eventually contaminated shoreline en-

vironments. By June 3, nearly 215 km of coastline had been oiled; 60 km received moderate to heavy accumulations. As part of spill control activities, at least 2000 tons of dispersants were applied around the wreck site. Further information concerning the circumstances of the spill and related cleanup activities is presented by Gundlach and Hayes (1977).

METHODS OF STUDY

Coastal environments affected by the Urquiola spill were studied from 17 May to 19 June 1976. A total of 99 observation stations were set up along the coast (see Gundlach, et al., in press). From 4-10 June 1976, four representative coastal environments were studied in detail (described below) to determine the biological impacts of oil on specific communities. A brief follow-up survey was completed on 1 and 2 May 1978.

This paper describes biological observations at the following locations (Fig. 2): 1. a fine-to medium-grained sandflat at Santa Cristina (Station B1), 2. a salt marsh within the Rio del Burgo estuary (B2), 3. a fine-grained mud flat at Puentedeume (B3), 4. an intertidal rocky shore at Porto Cobo (UQA-9), 5. a rocky shore at Playa de Ber (UQA-20), and 6. a fine-sand beach at Raso (UQA-22). A mud flat within the Ria de Betanzos was surveyed as a control site.

At station B1, four transects were run from low to mid-water marks. At stations B2 and B3, a single transect was completed from low to high water marks. Equidistant sampling sites were established along the transect. At each site, replicate 30 cm x 30 cm x 25 cm volumes of sediment were sieved through 0.8 cm mesh. Macrobenthic fauna were removed from the sieve and placed in polyethylene bags containing 70% ethanol. Examination was performed within 3 hours of capture. Organisms were measured, counted, and examined for degree of damage.

RESULTS

Santa Cristina Sandflat (B1)

The sandflat (100 m x 300 m) at Santa Cristina is located 7 km from the wreck site. Sediments are primarily medium- to fine-grained sand (0.3 - 0.5 mm) with coarser material underlying the surface sediments. At the time of the spill, the flat appeared oil stained, but without thick accumulations. However, along the beach face, a 5 m band of heavily-oiled sediment was present. A sketch of the area at the time is presented in Figure 3. Sand within the tidal flat exuded an oil sheen when rinsed with clear sea water.

Infauna of the area consisted primarily of the edible cockle, *Cerastoderma edule*, bivalves, *Scrobicularia plana*, *Venerupus decussata*, *Tellina tenuis*, and polychaetes, *Arenicola* and nereids. Table 1 presents population estimates and percent mortality at Santa Cristina. *C. edule* was by far the most abundant species, having a total estimated population of 4.5 million. The zonation pattern of all species is illustrated in Figure 4. The abundance and distribution of *C. edule* and *S. plana* are illustrated in Figure 5.

Cerastoderma edule, living within the upper 5 cm of sediment, was most severely affected during the spill, exhibiting 70% mortality (3.1 million individuals). Scrobicularia plana, occurring to a depth of 10 cm, suffered a lower mortality (30%) as did Tellina tenuis (19% mortality), whose population was restricted to the more muddy, low intertidal region on the flat. Thousands of oil-stained shells littered the surface of the flat (Fig. 6). Close examination revealed that the siphonal area on the posterior margin of the cockle shells was oil-stained to varying degrees. Dead cockles consistently exhibited a greater degree of staining than did living cockles. When placed in a water-filled trench, surviving cockles pumped slowly and irregularly when observed for a 15 minute period, suggesting sub-lethal impairment of their nervous systems. Nassarius reticulatus, the mud snail, was seen clumped about sub-tidal tubular green macroalgae (Enteromorpha) and suffered no apparent population mortality (Table 1).

The effects of the spill on polychaete populations in the area was difficult to determine. As experimentally observed, the fleshy corpses of these polychaetes decompose within 10 days following death. Since this study began 2 weeks after the initial spill occurred, reliable population estimates were impossible to assess. Surviving macrobenthic polychaetes (the sedentary Arenicola and errant nereids) appeared lethargic in their efforts to burrow back into the sediment, but sub-lethal impairment was difficult to substantiate. No attempt was made to estimate the meiobenthic polychaete population, which may have been the more predominant annelid form on this sand flat.

This area was revisited on 1 May 1978. No oil was observed on or below the surface of the sand flat or beach face. Analysis of 4 replicate samples revealed a reduction in species diversity and population. Where before, an average of 457 individuals of C. edule/m^2 existed, now only 114 per square meter were found. Full results of the second survey are presented in Table 2.

Rio del Burgo Estuary (B2)

Station B2 is a salt marsh environment located within the Rio del Burgo estuary (Fig. 2). Sediments of the area are composed of fine silts and clays. High fringe vegetation consisted of Juncus and Spartina grasses, while Zostera, eel grass, predominated in the lower marsh. At the time of the spill, the area was moderately contaminated by oil. Thick pools of oil accumulated along the high marsh fringe. Oil seeped into crab burrows, penetrating 15-20 cm deep into Spartina-covered mud-mounds at the upper reaches of the marsh. Most of the high marsh grasses were completely oil-blackened. A heavy oil sheen was observed along much of the lower marsh.

Species composition was similar to that of the Santa Cristina sand flat. Table 3 presents the population estimates and percent mortality data for each species at this study site. Species zonation is presented in Figure 7. Again, Cerastoderma edule suffered high mortality, while Scrobicularia suffered a lower (20%) population reduction. Many recently dead littorinid snails accumulated in the lower marsh area. Very few littorinids were found among intertidal

Spartina, where they would be expected to occur. The shore crab, Carcinus maenas, was found in two distinct regions of the marsh. Adult forms occurred at the high marsh region in burrow systems excavated within the Spartina covered mud-mounds; juveniles moved about over the lower muddy regions. Adults were oil coated; while juveniles were not, possibly indicating a recent molt. Surviving crabs seemed to suffer no impairment of locomotor function, and escape responses seemed to be unaffected.

Nereid population densities were nearly 40% lower than in the Betanzos control area. Nereids extricated from the heavily-oiled silty substrate writhed vigorously when placed in water containing an oil sheen, but exhibited normal locomotor rhythm when placed in clear water.

By the end of the first survey on 10 June 1976, new growth was visible on much of the previously-blackened marsh grass. By the second survey in 1978, most of the high marsh grasses appeared normal. However, the 1-2 m fringe area along the tidal flat/marsh interface had not fully recovered. Only short stubs of dead grass were present. A light oil sheen was still visible along much of the fringe. Several oil globs, 10 x 15 cm, were found in one previously-oiled area.

Puentedeume Marsh/Tidal Flat (B3)

Station B3 is a mud flat having a band of fringing marsh grasses. Its location is depicted in Fig. 2. Sediments consist mostly of silts and clays. Juncus and Spartina predominated in the high marsh fringe. Zostera grew over the entire lower mud flat.

Oil deposition was heavy along the fringing marsh. All grasses were oil blackened. An oil coating of 2-3 cm was commonly observed at the base of these grasses. Tidal flat sediments rinsed in clear sea water exuded an oil sheen. As the tide flooded the area, small oil globules and an oil sheen were observed to rise out of the sediment and become mobilized by tidal currents.

While community structure at Station B3 was similar to that observed at *Santa Cristina* and Rio del Burgo, species composition was distinctly different (Fig. 8). Species diversity was higher here than at any other station. In addition to the genera and species indicated in Table 4, thirteen other molluscan species were identified from sub-tidal samples (Table 5). At Puentedeume, as at Rio del Burgo, Cerastoderma edule and Littorina littorea suffered the highest mortalities. Scrobicularia plana, the predominant bivalve in this habitat, suffered 25% mortality (comparable to its mortality at other stations). Mortality in the gastropod, Hydrobia, was difficult to assess in the field because of their minute size (less than 6 mm). Observation of lomotion and orientation responses in polychaetes and crabs suggested that these organisms were unharmed. Small elvers (6.5 cm), which would be expected to be highly sensitive to spilled oil because of their high rate of oxygen consumption and high rate of metabolism (see Vernberg, 1972), were apparently unharmed.

Two years later, after returning to the station, a narrow (1 m) band of destroyed marsh grass was evident. Grasses previously only oil-blackened recovered fully. An oil sheen was apparent on the marsh surface,

and minor traces of mousse could still be found. No algae were present on the mud flat, probably due to seasonal differences rather than the effects of the oil spill.

Porto Cobo (UQA-9)

The station at Porto Cobo is comparable to a typical New England rocky intertidal habitat. Sediments consist of mixed sand and gravel with outcropping bedrock along the low-tide terrace. Oil coverage at the time of the spill was heavy along the upper intertidal zone and on the rocks.

The effects of the spill were not as dramatically apparent here as compared with other stations but were still important. Shore crabs, Carcinus maenas, were oil blackened, but still exhibited normal shadow- and escape-responses. A school of small fish, seen swimming nearshore, exhibited variable behavior. While most fish swam, changing direction sharply and in a well-coordinated fashion, several individuals lost contact with the main school and became stranded on shore. When returned to the water, these individuals swam about, changing direction erratically, indicating sub-lethal damage. Nudibranchs, numerous within lightly-oiled tidepools, showed no response upon being prodded with a blunt instrument. The limpets, Acmea sp., Patella intermedia, and Patella aspera, were loosely attached to the rocks, being easily removed by hand. The oil seemed to interfere with their adhesive capability.

Playa de Ber (UQA-20)

Playa de Ber is a relatively exposed, fine-sand beach with outcropping bedrock on the low-tide terrace (Fig. 2). On our first visit during the spill, a large oil pool covered the low-tide terrace and much of the beach face. Sediment on the low-tide terrace was totally saturated with oil. Rocks were completely oil blackened on their shoreward face but generally free of oil on the side exposed to wave activity. Barnacles, limpets and intertidal macroalgae were oil covered. Mortality in amphipods was dramatic. Their bodies accumulated at the high tide swash line in high concentrations.

Revisiting the area two years later, we found minor repopulation of the sheltered rocks by intertidal fauna. Barnacles and limpets were not commonly observed. Patchy tar remained on the sheltered side of outcropping rocks. A large percentage of the exposed rock surfaces was covered by Enteromorpha, a tubular green alga. Living mussels and limpets were also observed on the wave-exposed rock surfaces. Between the rocks, a 4 m x 2 m x 30 cm patch of heavily-oiled sediment remained, possibly providing a source of continuous low-level hydrocarbon contamination to the adjacent areas.

Raso (UQA-22)

Raso is a flat, fine-sand beach located within the Ria de Ares. At the time of the spill, a 1 cm thick coat of oil covered the entire intertidal zone (Fig. 9a). As a result of the oiling, the high tide swash

line was littered with thousands of dead amphipods (Fig. 9b). We estimate that over 125,000 amphipods were killed at this particular beach.

Our follow-up survey two years later, uncovered no trace of oil. However, eight quadrat analyses along the upper beach face revealed only two amphipod individuals. Apparently, repopulation of this area is very slow.

DISCUSSION

This study was limited by the short time given for preparation and field work and the unfortunate lack of baseline data. It should also be noted that the extensive offshore use of dispersants complicated evaluation of the singular effects of spilled oil. Biological damage could have been caused by the spilled crude oil, a mixture of oil and dispersant, or, though unlikely, the dispersant alone.

In our field study, quantitative examination of the Santa Cristina sand flat, the Rio del Burgo marsh, and the Puentedeume mud flat revealed a basic similarity in these mollusc and polychaete dominated communities. Quadrat sampling and analysis revealed that *Cerastoderma edule* was the macrobenthic species most susceptible to the lethal effects of spilled oil, suffering from 56-70% mortality. During the *Torrey Canyon* spill, *Cerastoderma* similarly suffered the greatest mortality among affected biota (Smith, 1968).

We consistently observed that *S. plana*, a deeper burrowing bivalve, suffered only a 20-30% population reduction. In addition, *L. littorea*, a high marsh species living on *Spartina* blades, was completely eliminated in the Rio del Burgo, while the sub-tidally occurring *N. reticulatus* showed high survivorship. It appears then that molluscs living at the water/sediment interface (*C. edule*, *L. littorea*) suffer the highest mortalities. Burrowing organisms living deeper below the sediment (*S. plana*, *V. decussata*, *T. tenuis*) or those living sub-tidally (*N. reticulatus*) seem to survive the effects of spilled oil to a greater degree than do surface-dwelling organisms. Therefore, while vulnerability to oil may appear species-specific, it may also be influenced by habitat preference. This hypothesis can be supported by a comparison of the size class versus the number dead for *C. edule* (Fig. 10). The pattern is similar on both graphs. The number of dead cockles is proportional to the number of individuals comprising that size class interval. If death in *C. edule* were due to disruption of some physiological process, then the pattern would not be similar. Smaller individuals, metabolizing at a much higher rate than larger individuals of the same species (Vernberg, 1972) would be expected to suffer higher mortalities. Since this is not the observed pattern, some other factor must be responsible for the death of *C. edule*. The physical clogging of respiratory membranes by oiled sand particles is suggested by the fact that dead cockle shells consistently appeared more heavily oil-stained in their siphonal region than did living cockles (see Nelson-Smith, 1972).

The impact of oil on polychaete populations is unclear because of a lack of previous baseline studies for each area and the rapidity with which fleshy bodies decompose in the marine environment. But it seems

clear that survivors suffered no short sub-lethal damage, as was observed in cockles and small, low-intertidal fish.

It was also difficult to assess the effects of the spill on the crab populations since exoskeletons of dead crabs may be transported by tidal currents and aggregate at the high water line. However, surviving crabs seemed to suffer no sub-lethal impairment to their normal behavior patterns. The fact that juvenile crabs conspicuously lacked the black coating that typified their older conspecifics may merely reflect that molting occurred during the interim between inital oiling and our investigations.

High mortality in L. littorea may have occurred as a result of the interference of oil with this species' ability to successfully adhere to its substrate. After death, these organisms might then be translocated within the estuary by the motion of the tide (Nelson-Smith, 1972). This would explain the large accumulations of L. littorea at the low water line in the Rio del Burgo marsh. Many limpets (Acmea sp., Patella spp.) affected by the oil may have been able to remain in position on the rocks, though loosely attached because of their location in a generally low-wave energy environment.

CONCLUSIONS

From our observation of coastal environments affected by the Urquiola spill, we are able to conclude the following:

1. Edible cockle (Cerastoderma edule) populations suffered consistently high mortality ranging from 50-70% after the spill, probably as a result of the physical clogging of respiratory membranes by oiled particles.

2. Surviving cockles exhibited irregular pumping rates and a conspicuous absence of normal burrowing behavior.

3. Other bivalves (Scrobicularia plana, Tellina tenuis, Venerupus decussata), exhibited mortalities ranging from 19% to 30%.

4. Sub-lethal impairment of adhesive capability was observed in L. littorea and several species of limpets.

5. Sub-lethal impairment, in terms of orientation responses, in small, low-intertidal fish was observed.

6. Sub-lethal damage to nudibranchs was evidenced by their complete lack of tactile responses when prodded by a blunt instrument.

7. Surviving decapod crabs and polychaete annelids seemed to be unaffected by the spilled oil.

8. Amphipod populations at the two fine-sand beaches, Playa de Ber and Raso, were completely destroyed by the oil, probably as a result of smothering. Limited recovery was observed 2 years later.

9. The pre-spill structure of polychaete communities is difficult to assess because of rapid body decomposition following death. However, surviving lugworms (Arenicola) and nereid worms seemed to suffer no long-lasting impairment to locomotion.

10. Marsh grasses were subjected to heavy oil cover during the spill. Two years later, complete recovery was observed except for a narrow band of fringing marsh where the oil originally formed thick pools.

11. Two years after the spill, oiled rocky intertidal areas generally showed no signs of oil contamination. However, at de Ber, tar patches remained, and the number of organisms observed was low.

ACKNOWLEDGEMENTS

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Table 1. Population and Percent Mortality
Santa Cristina, 1976

	Population Density (No./Sq. m)	Mortality (%)
Cerastoderma edule	457	70
Scrobicularia plana	85	30
Nassarius reticulatus	48	0
Tellina tenuis	17	23
Venerupus decussata	5	19
Hydrobia	--	--
Arenicola	4	--
Nereis	2	--

Table 2. Population and Percent Mortality
Santa Cristina, 1978

	Population Density (No./Sq. m)	Mortality (%)
Cerastoderma edule	114	0
Scrobicularia plana	3	0
Carcinus maenas	3	0

Table 3. Population and Percent Mortality
Rio del Burgo, 1976

	Population Density (No./Sq. m)	Mortality (%)
Cerastoderma edule	200	56
Scrobicularia plana	89	20
Nereis	44	--
Carcinus maenas	38	38
Littorina littorea	15	100
Venerupus decussata	11	0
Hydrobia	11	--

Table 4. Population and Percent Mortality
Puentedeune, 1976

	Population Density (No./Sq. m)	Mortality (%)
Hydrobia	800	--
Nereis	75	--
Scrobicularia plana	70	25
Carcinus maenas	14	--
Littorina littorea	10	50
Anguilla anguilla	7	0
Cerastoderma edule	5	50
Mytilus edulis	3	0

Table 5. Molluscan Species also found at Puentedeume.

Barnea candida

Donax vitalis

Gibbula magus

Littorina littorea

Monodonata lineata

Mytilus edulis

Nassarius reticulatus

Natica catina

Ocenebra erinacea

Ostra edule

Spisula solida

Tellina tenuis

Trivia monacha

Venerupus decussata

Venerupus pallustra

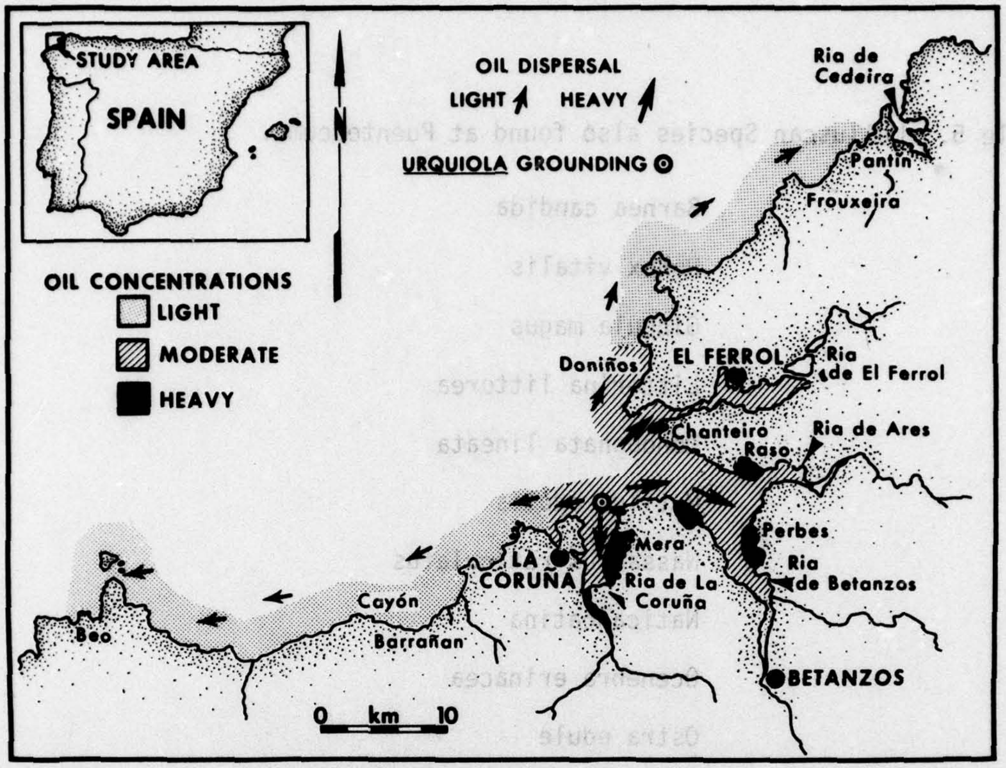


Figure 1. Location map for the URQUIOLA oil spill. In total, 215 km of shoreline was oiled; 60 km was moderately to heavily oiled (from Gundlach and Hayes, 1977).

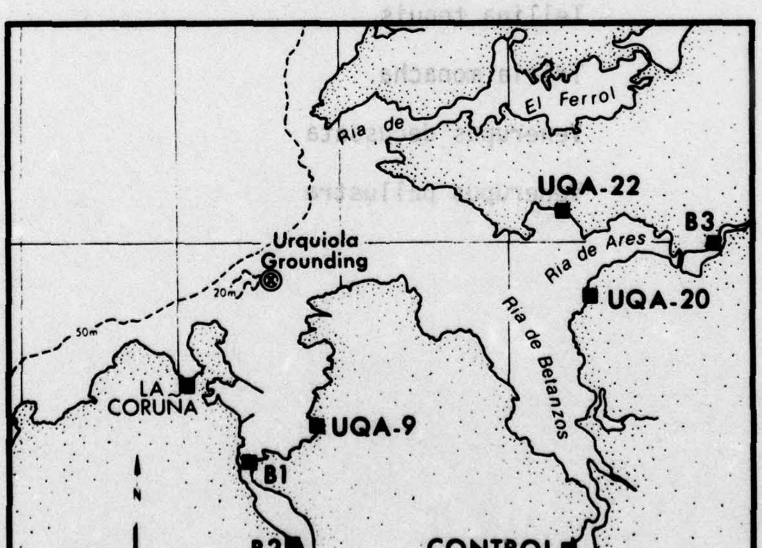


Figure 2. Location of study sites used in this report. Stations B1 to B3 and the CONTROL area were studied in detail using routine quadrat analysis methods.

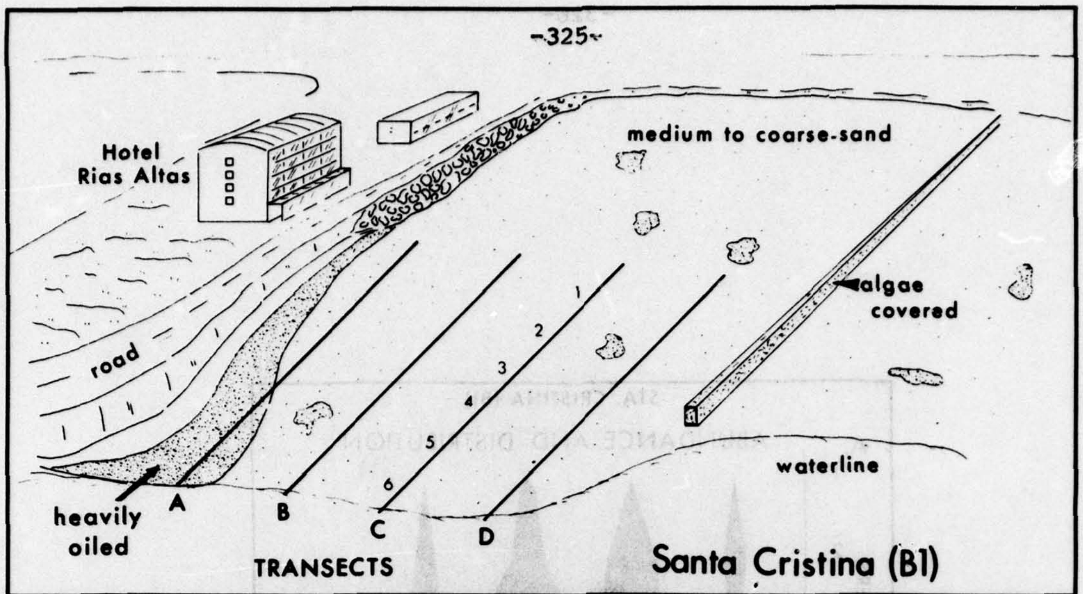


Figure 3. Sketch of the Santa Cristina sand flat (Station B1) on 2 June 1976. Transects were placed 25 m apart. Replicate samples at each of six stations along the transect were taken.

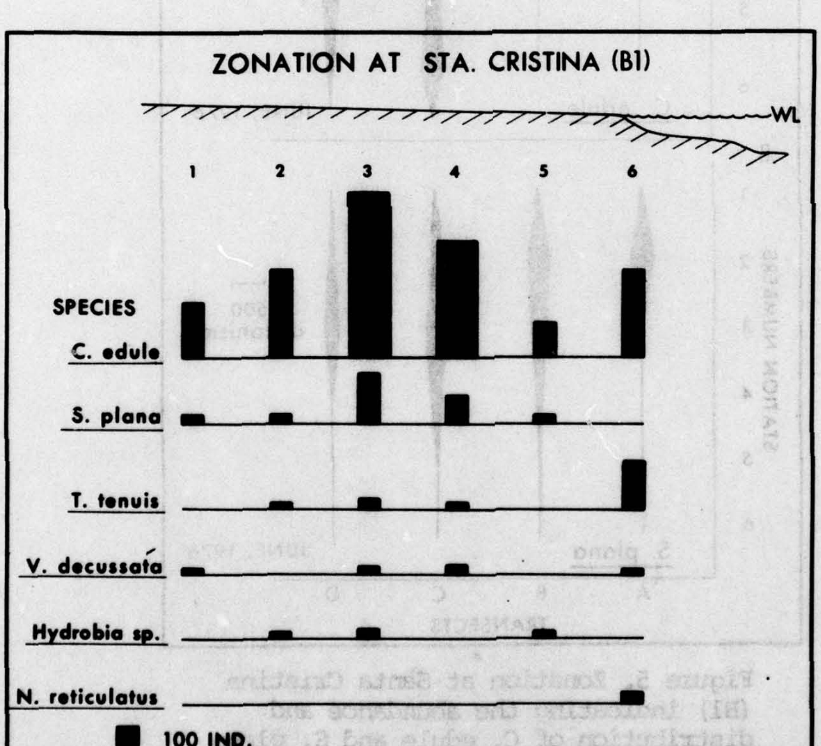


Figure 4. Zonation at Santa Cristina (B1) indicating the abundance and distribution of species along a transect.

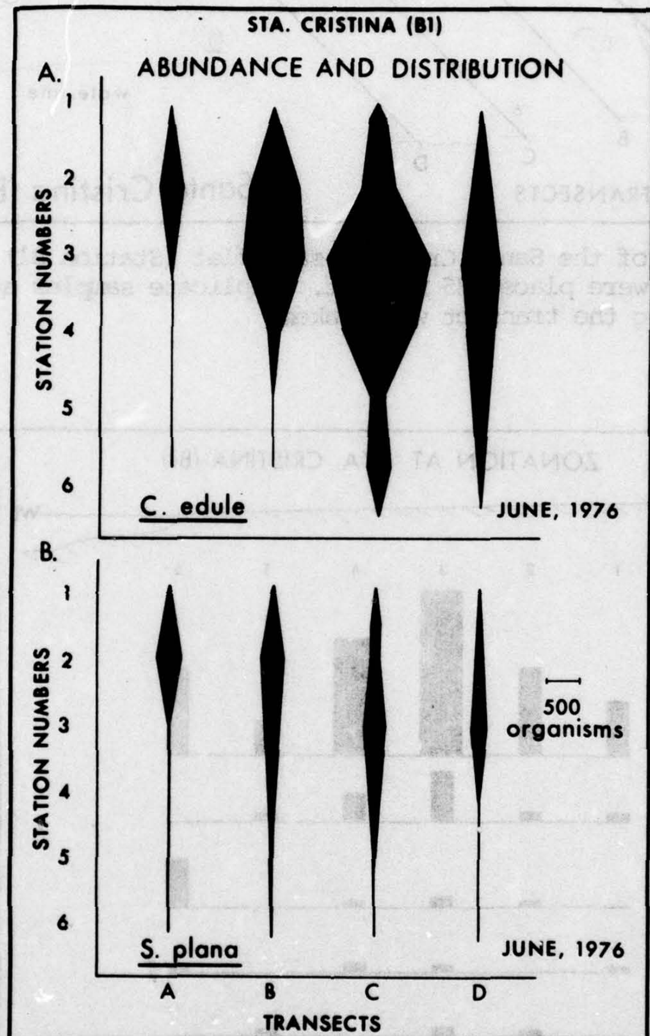


Figure 5. Zonation at Santa Cristina (B1) indicating the abundance and distribution of C. edule and S. plana along each of the four transects.

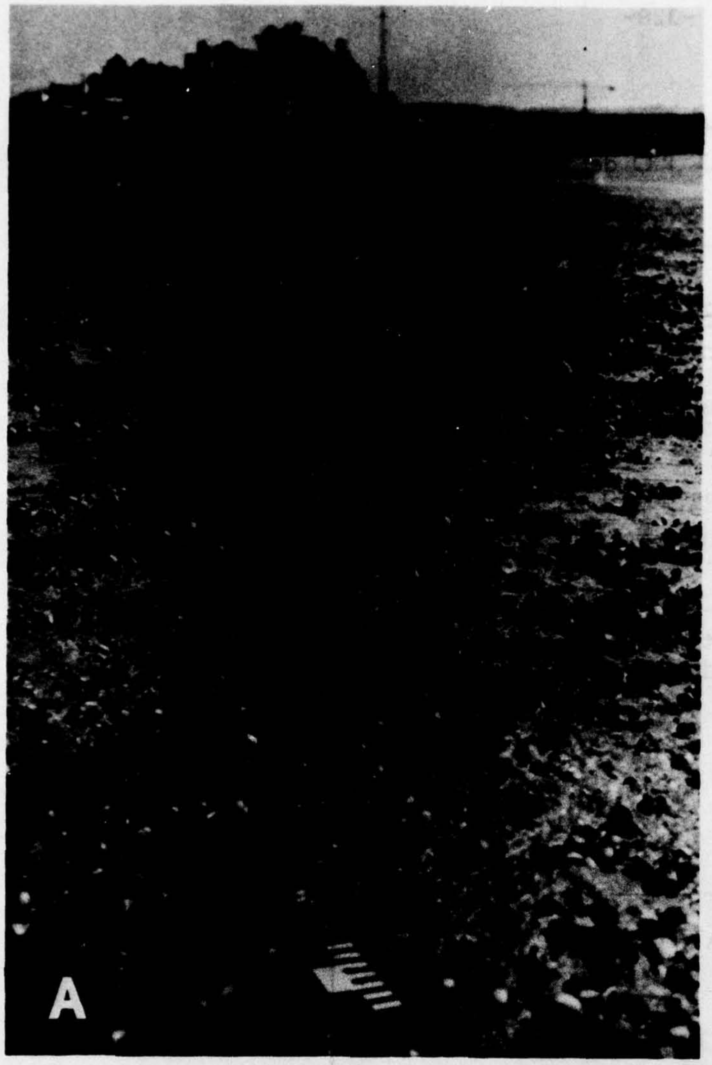
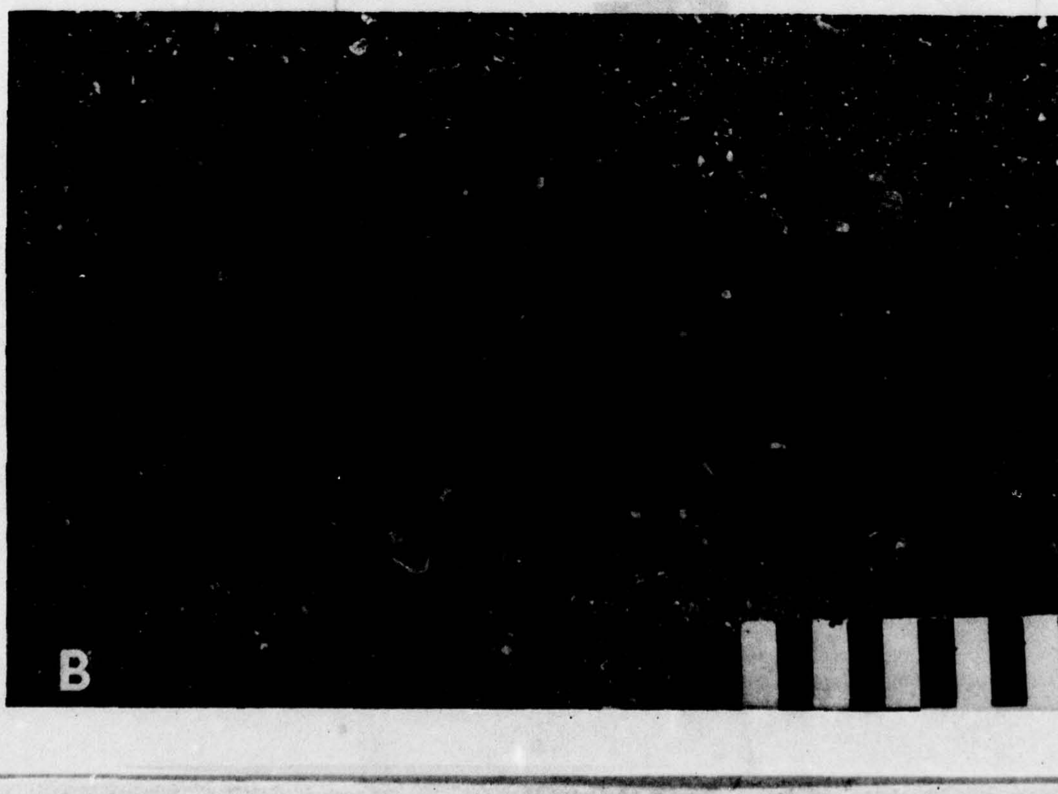


Figure 6. (A) The sand flat at Santa Cristina was dramatically affected by the spill. Millions of dead cockle shells littered the beach as shown here. (B) Close-up photograph of dying cockles (Cerastoderma edule).



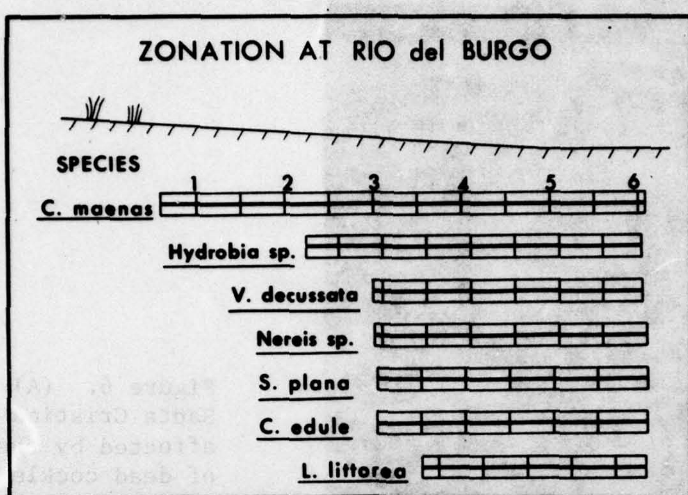


Figure 7. Zonation at Rio del Burgo (B2) indicating the distribution of species along a transect 300 m long.

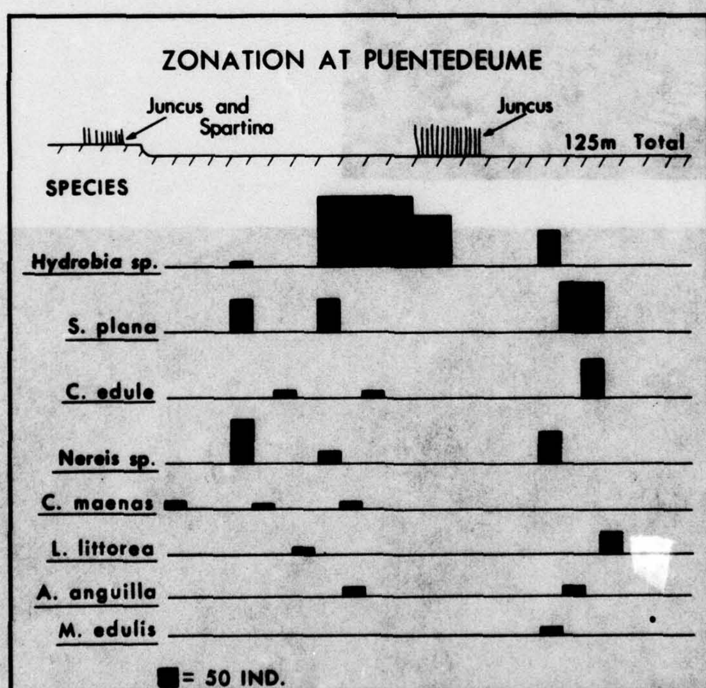
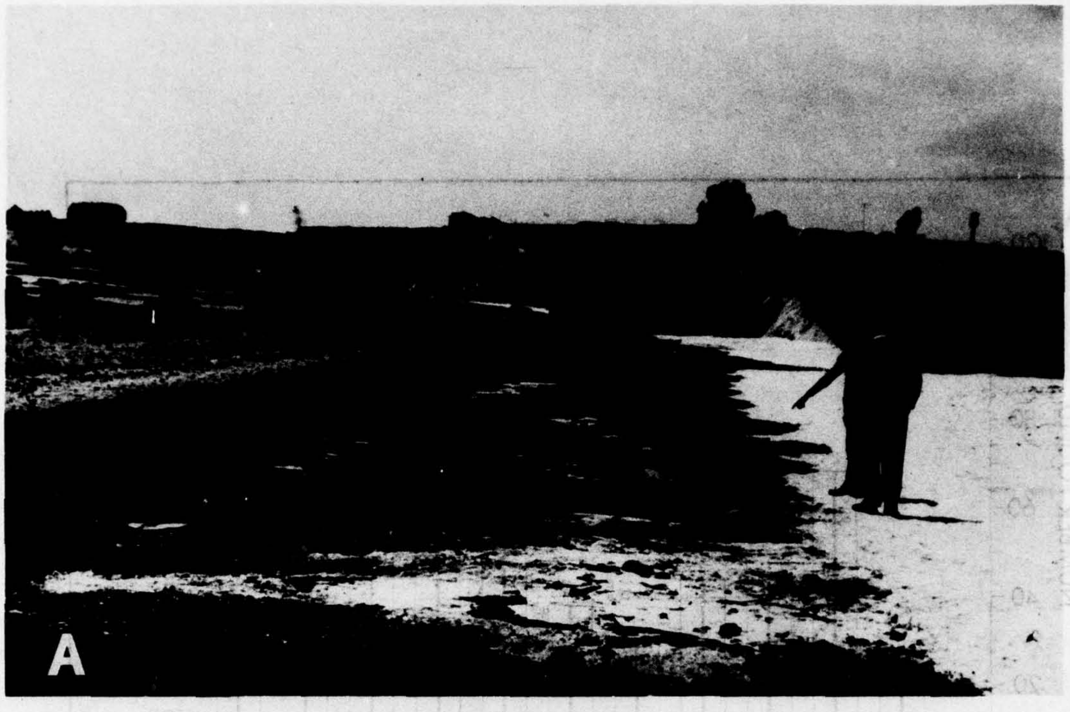


Figure 8. Zonation at Puentedeume (B3) indicating the abundance and distribution of species along a transect 125 m long.



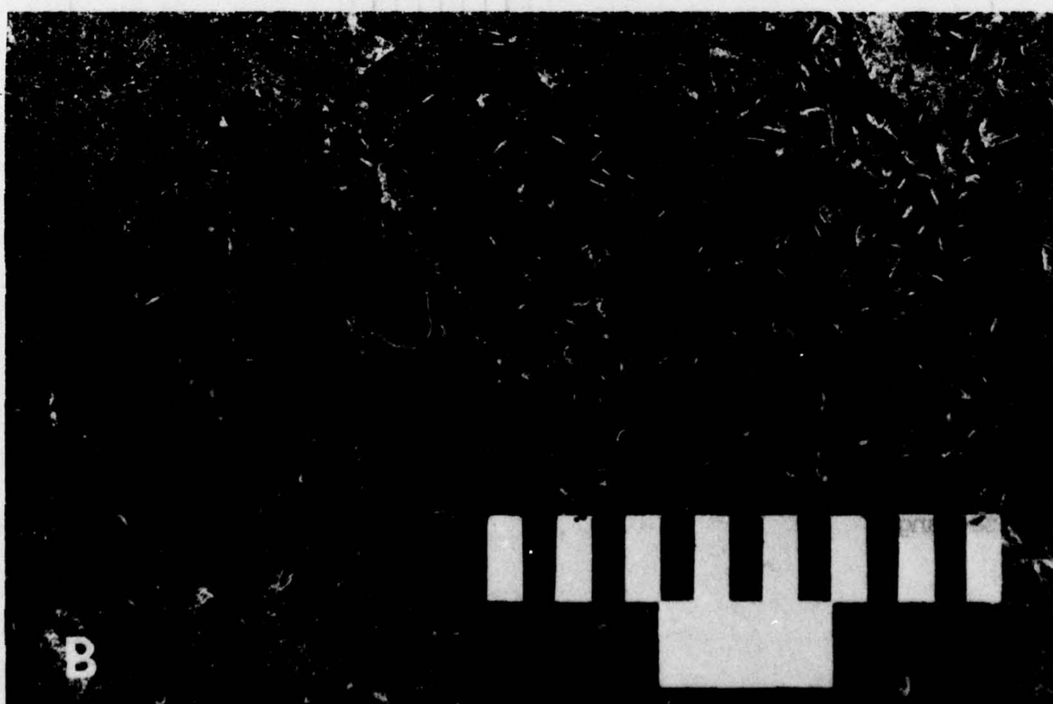


Figure 9. (A) Heavily oiled beach at Playa de Raso (UQA-22) on 19 May 1976. The dead amphipods pictured in (B) were located along the high tide swash line.

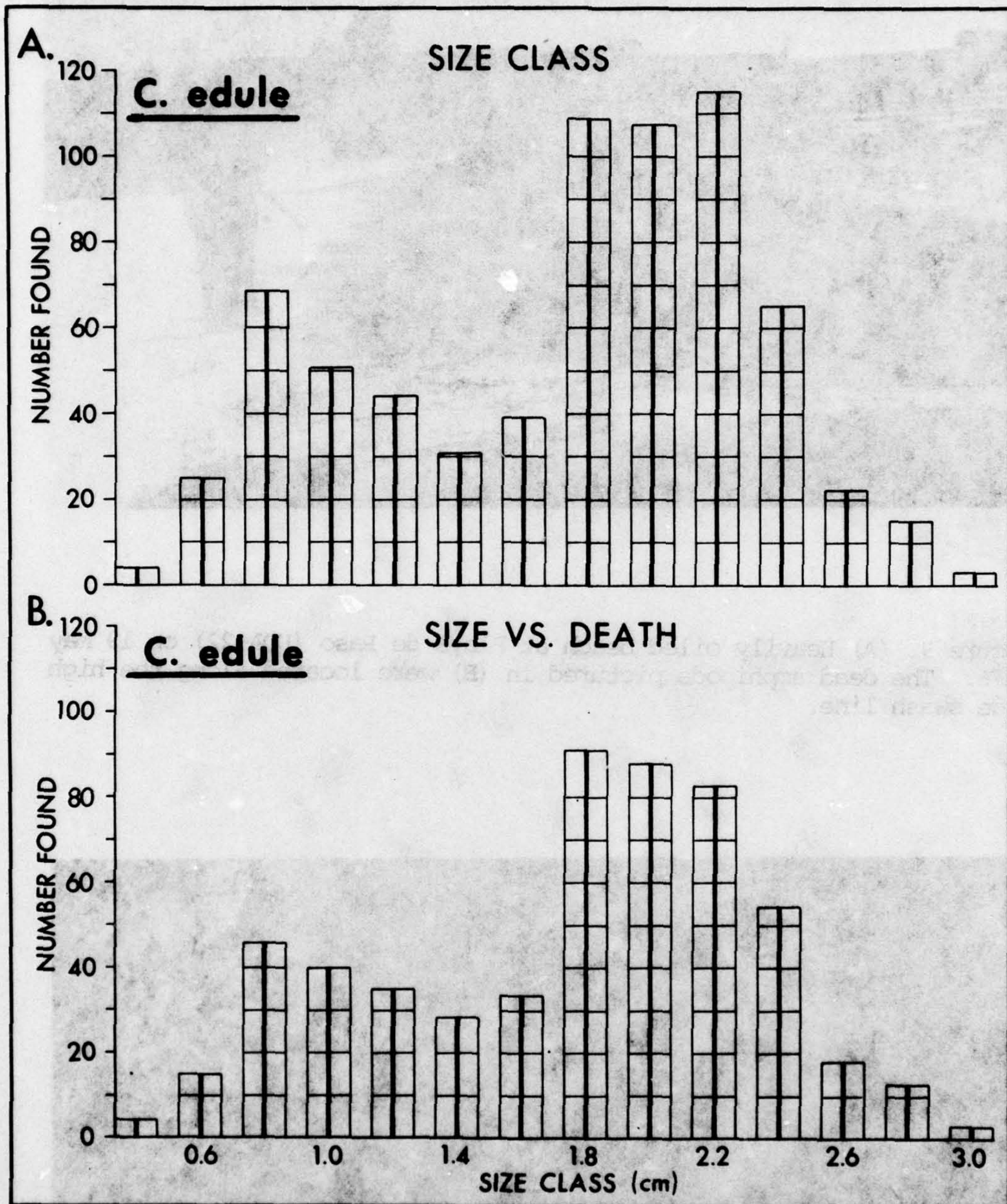


Figure 10. These histograms, based on an analysis of samples taken at Santa Cristina, indicate that the number of dead cockles, Cerastoderma edule, within each size-class interval, is proportional to the number of individuals comprising that size class throughout the entire population size-range.

FATE AND EFFECT OF BUNKER C OIL SPILLED BY THE USNS POTOMAC IN MELVILLE BAY - GREENLAND - 1977

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ABSTRACT

On August 5, 1977, 380 tons of Bunker C fuel oil were spilled in Melville Bay, off Northwest Greenland. Studies of its fate and effects were conducted shortly after the spill occurred. The primary weathering mechanisms were evaporation and dissolution. Alkanes up to n-C_{17}, and substituted naphthalenes, were depleted as much as 50 to 100 percent after 15 days of weathering. Tar flakes were observed sinking into the water column 10 days after the spill. Increased values of petroleum hydrocarbons in the water column were found in the immediate vicinity of the spill. Microbial degradation of the oil did not occur during the first two weeks. No immediate effect on the zooplankton was observed, but ingested oil was found in copepods and amphipods. No oiled birds and seals were observed, but oiled seals have been reported by local hunters. Oil from the seals has been analysed, and the oil might be identical to the oil spilled from the POTOMAC.

INTRODUCTION

On August 5, 1977, the USNS POTOMAC was being escorted by the USCGC WESTWIND, in intermittent dense fog, through the scattered sea ice of Melville Bay in the northeastern part of Baffin Bay off Greenland. At 0430 a.m. local time, it was discovered that a tank containing about 380 tons of Bunker C fuel oil had been holed by an iceberg or "growler," and almost all the fuel in the holed tank was spilled.

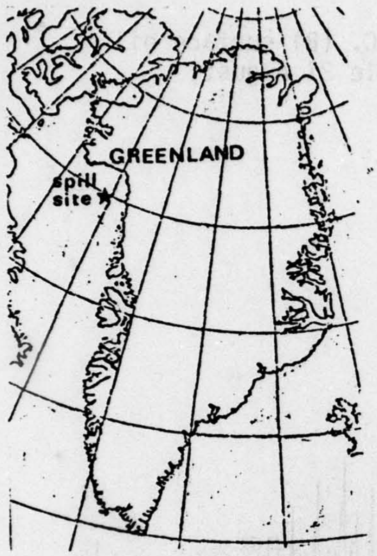


Figure 1. Location of spill site.

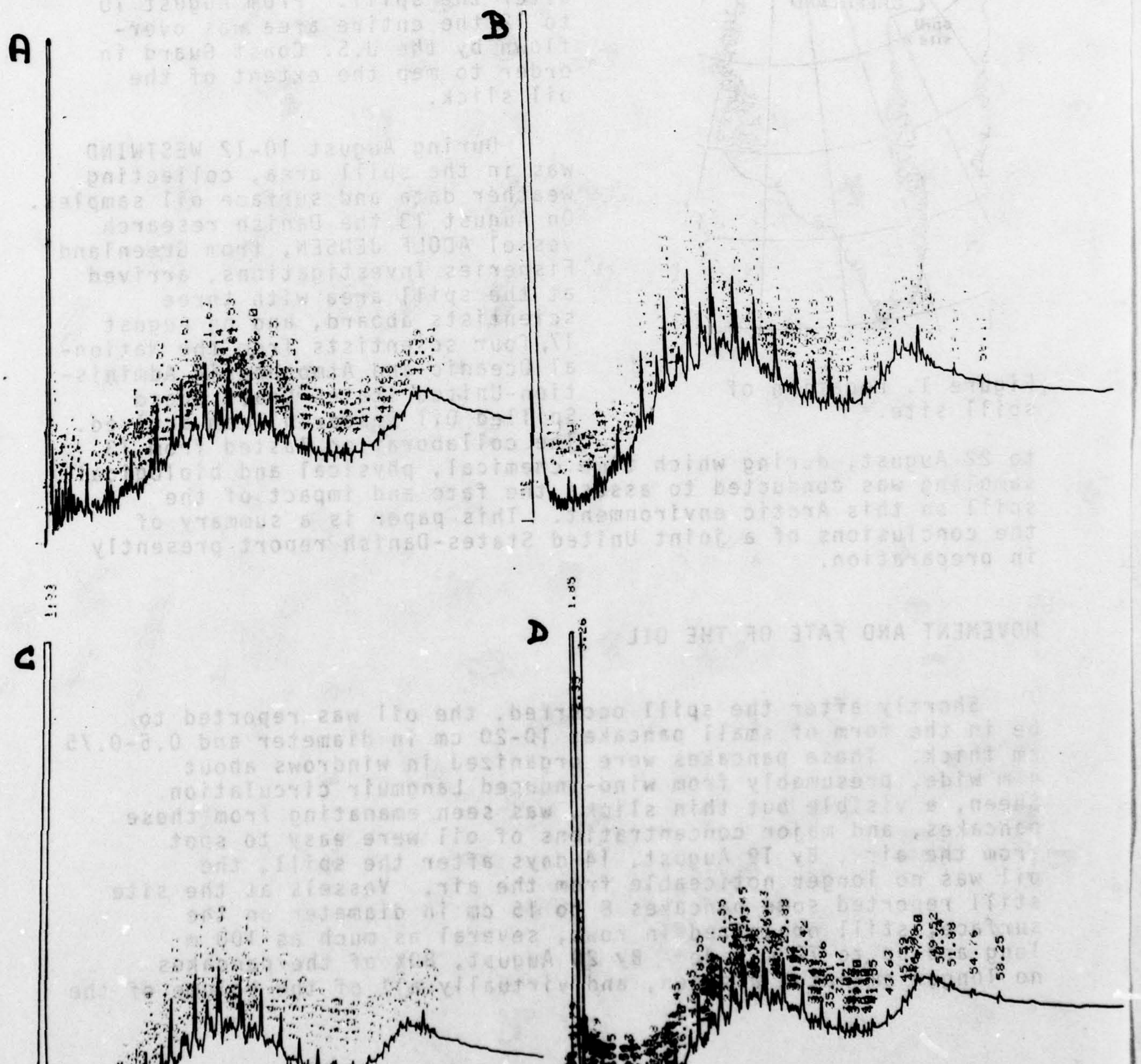
Calm seas, with waves of 0 to two feet, and light winds of 0 to seven knots, kept the oil from dispersing for several days after the spill. From August 10 to 12 the entire area was overflown by the U.S. Coast Guard in order to map the extent of the oil slick.

During August 10-12 WESTWIND was in the spill area, collecting weather data and surface oil samples. On August 13 the Danish research vessel ADOLF JENSEN, from Greenland Fisheries Investigations, arrived at the spill area with three scientists aboard, and on August 17, four scientists from the National Oceanic and Atmospheric Administion-United States Coast Guard Spilled Oil Research Team arrived. The collaboration lasted from 13 to 22 August, during which time chemical, physical and biological sampling was conducted to assess the fate and impact of the spill on this Arctic environment. This paper is a summary of the conclusions of a joint United States-Danish report presently in preparation.

MOVEMENT AND FATE OF THE OIL

Shortly after the spill occurred, the oil was reported to be in the form of small pancakes 10-20 cm in diameter and 0.5-0.75 cm thick. These pancakes were organized in windrows about 4 m wide, presumably from wind-induced Langmuir circulation. Sheen, a visible but thin slick, was seen emanating from these pancakes, and major concentrations of oil were easy to spot from the air. By 19 August, 14 days after the spill, the oil was no longer noticeable from the air. Vessels at the site still reported some pancakes 8 to 15 cm in diameter on the surface, still organized in rows, several as much as 100 m long and up to 70 m wide. By 20 August, 80% of the pancakes no longer emanated a sheen, and virtually all of the volume of the

Figure 2. Gas chromatograms of (A) POTOMAC Bunker C, (B) surface oil sample 10 August, (C) surface oil sample 21 August, (D) surface oil sample 1 October.



remaining pancakes was submerged. Many pieces about the size and shape of cornflakes were observed at the water surface and in the water column, with a large number of subsurface flakes reported on 19 August. By this time the surface oil had become spongy in texture, although it was not undergoing water-in-oil emulsification, or "mousse" formation. Even after two weeks of weathering, less than 5% water was found in the surface oil.

The spilled oil did not reach the shore. Icebergs in the vicinity of the spill were examined by the U.S. Coast Guard to determine if oil was adhering to them. The oil stayed away from the icebergs, probably because of the melting of the ice.

Horizontal Advection

Horizontal advection of the spilled oil was influenced by the general circulation, or permanent currents, upon which the local effects of wind stress and waves are superimposed, tending to move the oil independent of the surrounding water. Surface currents were found to be of small magnitude. The wind-induced currents and wave interactions probably contributed less than 5 cm/s to the oil's horizontal advection, and tended to cancel out after a few days because of the random nature of this effect. The general surface drift appeared to have been westerly at about 5 cm/s, which indicates that the oil was not transported far from the spill site, i.e., less than 40 nautical miles over a 2-week period.

The elongated slick pattern (8 nautical miles in length) was probably caused by spillage over a period of time. Once generated, this pattern was then advected by local currents in random directions, depending primarily on winds with a net set to the northwest from the permanent currents. Advection of the oil by the surface currents did allow a large surface area to be exposed to the oil. The area exposed was estimated to be about 500 square miles, based on direct observations of the oil slick and on current measurements.

Vertical Movements

Measurements showed that the water column could be considered as a two-layer fluid system, with the top layer being 10-20 m thick. The specific gravity (s.g.) between the two layers changed from 1.024 to 1.027. The initial s.g. of the oil was 0.96. As the oil weathered, it was observed to sink into the water column, indicating an increase in s.g. to more than 1.024. It cannot be assumed that the specific gravity stopped increasing as soon as the oil sank below the surface; chemical analysis of the one subsurface (bongo) sample indicated that weathering in fact probably increased dissolution of sparingly soluble aromatic components. The original

blend of the spilled oil contained 55% pitch with a s.g. of 1.055, which can be taken as an upper limit for the specific gravity of the weathered oil. It is believed that the weathered oil eventually sank to the bottom in the area of the spill. Below 20 m, sinking would have been accelerated by the greater compressibility of the oil as compared with the water; and by the nearly uniform density of the lower water layer. Historical geostrophic current data indicate that velocities are low (2% of the surface currents) in this deep layer. Thus, once the oil had sunk below 20 m, it would not have advected horizontally to any significant extent during the several weeks that it would take to reach the bottom. At a mean fall velocity of 1 cm/min, it would take less than 50 days for the oil to reach bottom in most areas of Melville Bay.

Weathering of Surface Oil

Samples of surface oil were collected from 10 to 24 August. Two additional samples were collected by local people after this period, and are referred to as having been obtained on 18 September and 1 October, although those dates may not be completely accurate.

Gas chromatography, mass spectrometry, and spectrofluorometry were used to fingerprint and investigate chemical changes in the spilled oil. Both gas chromatography and spectrofluoremetry confirm that all of the samples consisted of oil spilled by the POTOMAC.

Gas chromatograms of all samples of the spilled oil were quite similar except for some variability in the relative abundance of the more volatile and soluble components (Figure 2). The abundance of the n-alkanes for each spilled oil sample was normalized to that of n-C_{20}, and the relative changes over time were compared (Figure 3).

The variance of the points for n-alkanes less than n-C_{18} is much greater than for n-alkanes greater than n-C_{18}, and shows a trend of increasing depletion of lower molecular weight compounds in samples collected at later dates. The primary weathering mechanisms over the first 2 weeks were evaporation and dissolution. Components exhibiting vapor pressures equivalent to or greater than that of n-heptadecane (n-C_{17}), and substituted naphthalenes, were depleted by 50-100 percent after 15 days of weathering.

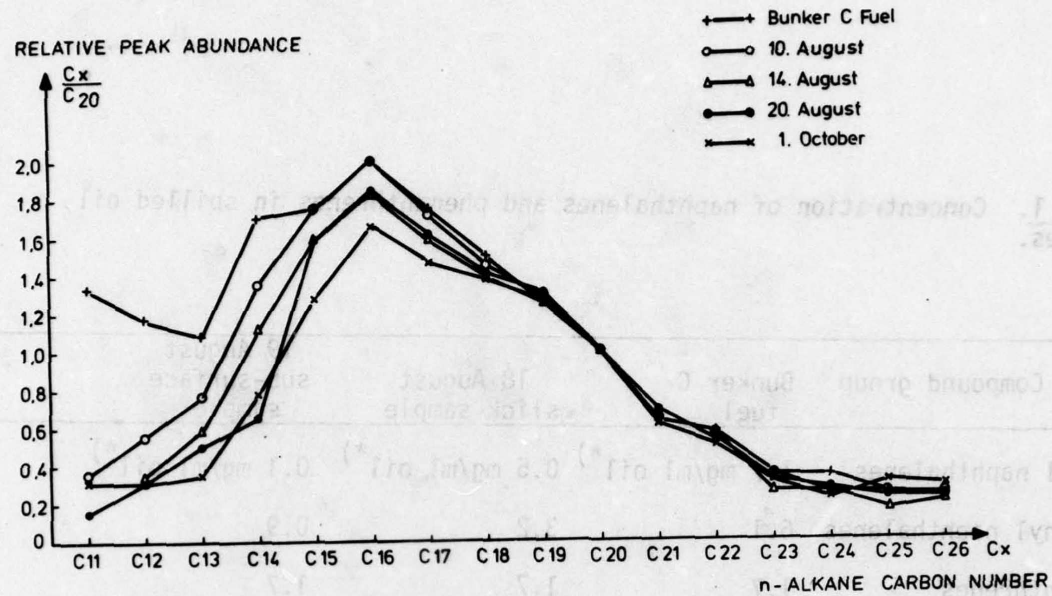


Figure 3. Relative peak abundance of n-alkanes for spilled oil samples.

The cold surface water temparatures (3-4^{o}C), light winds (0-7 knots), and the thick oil slick (up to 0.75 cm thickness) are all factors which tend to slow down evaporation rates, as compared to spills occurring in warmer waters, and this accounts for the loss of only the lightest compounds.

Five aromatic isomeric groups of compounds were quantified in the Bunker C fuel and in the spilled oil samples collected on 18 and 19 August (Table 1). The sample collected on 18 August was surface sample and the sample from 19 August was a subsurface sample collected in a horizontal Bongo tow. The 18 August surface sample was depleted in methyl napthalenes and dimethyl napthalenes, as would be expected from the known relatively rapid rates of evaporation and dissolution of these compounds. Absolute concentrations of phenanthrenes and methyl pehanthrenes in the oil slick samples appear to increase slightly with time. The evaporation and dissolution losses of the lower boiling compounds probably account for the apparent increase in the methyl phenanthrenes.

The subsurface sample collected on 19 August shows more extensive losses of the methyl and dimethyl naphthalenes, but similar concentrations of the phenanthrenes. The more extensive loss of the substituted napthalenes in the subsurface samples cannot be explained by enhanced evaporation alone. Once broken-down into smaller particles and dispersed into the water column, the spilled oil apparently weathered more rapidly, primarily by dissolution of the aromatic compounds.

Table 1. Concentration of naphthalenes and phenanthrenes in spilled oil samples.

Compound group	Bunker C fuel	18 August slick sample	19 August sub-surface sample
Methyl naphthalenes	1.7 mg/ml oil*)	0.5 mg/ml oil*)	0.1 mg/ml oil*)
Dimethyl naphthalenes	6.1	3.2	0.9
Phenanthrenes	1.7	1.7	1.7
Methyl phenanthrenes	3.3	3.8	[illegible].8
Dimethyl phenanthrenes	3.5	5.6	4.9

*) Concentrations reflect the sum of all isomers of the compound group.

Fluorescence examinations, on the other hand, showed that three-, four-, and five-ringed compounds were depleted to a larger extent than two ringed compounds. This contradicts the observation, by gas chromatography/ mass spectrometry, that naphthalenes decrease relative to phenanthrenes, but the fluorescence scan detects both polar compounds containing aromatic rings and simple aromatic compounds. The overall decrease in the three-, four-, and five ringed compounds has been observed elsewhere, and the apparent conflict in this case may be the result of differing behaviour of simple aromatic compounds and substituted aromatic compounds (Eastwood, 1977).

Gravimetric measurements of asphaltenes showed no significant changes from 10 to 21 August. Asphaltenes would not be expected to separate out by gravity settling, since their density is approximately 1.0, and their surface activity tends to keep them dispersed in the oil (Milgram, 1977). The tar flakes observed to be settling in the water column may have been caused by "sloughing" of the highly weathered "skin" that is known to form at the air-oil interface of pancakes.

The relative amounts of C_{17}/ pristane and C_{18}/ phytane were also calculated and showed no significant changes up to 21 August. The samples collected nearly two months after the spill showed no significant decrease, indicating no biodegradation of the oil.

Accomodation into the Water Column

Subsurface water samples were taken at 13 locations with 1-l bottles fitted with teflon-lined plastic caps, with a hole in the center of each. The teflon lining was penetrated by a spike when a messenger was dropped, allowing the bottles to fill. The water sample was extracted with hexane in the sampling bottle. The water samples were analysed using a spectro-fluorometric technique. Quantification was made with the original Bunker C fuel, obtained from the refinery, as the standard. The spilled oil contained a high percentage of heavy aromatic hydrocarbons, giving rise to fluorescence at long wavelengths. Its fluorescence characteristics differed significantly from those of lighter oils, and also from the pattern found in apparently unpolluted water. Therefore, fluorescence spectra exhibiting these properties could be traced to the POTOMAC oil in many samples, even though the concentrations were quite low. Combined results from different locations are shown in Figure 4.

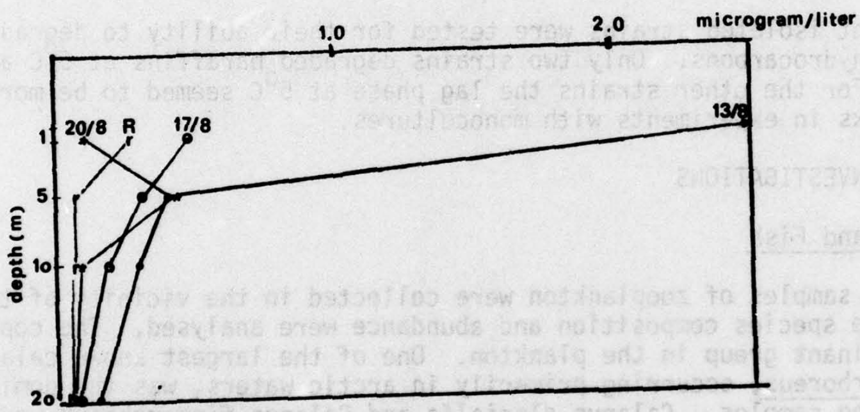


Figure 4. Petroleum hydrocarbons in subsurface water samples. Quantified as the amount of reference oil that give rise to the same fluorescence intensity at 310/400 nm (excitation/emission).

The fluorescence pattern of contaminated water samples deviated significantly from that of the spilled oil. Evidently, dissolution and, possibly, adsorption processes produced a different distribution of the petroleum hydrocarbons than that found in the water column a few days after the spill occurred.

Mass spectrometric analyses of water samples showed 0.050 ppb of selected aromatic hydrocarbons. In the reference oil the selected aromatics made up 0.8%. Assuming the same relationship to hold for the water samples, the total concentration, 6.2 ppb, found in the water column was quite low. Larger scale dispersion of the oil in the water column might have occurred during the eight days before the first sampling of the water.

Microbial Degradation

Water samples collected for microbiological examination showed small total numbers, and ever smaller numbers of oil-degrading, microorganisms. The estimated number of oil-degrading-microorganisms corresponded to less than 1% of the total number. No increase in total numbers or in oil-degrading microorganisms was found between 14 and 21 August. This confirmed the observed constant C_{17}/ pristane and C_{18}/ phytane ratios found in the surface oil samples.

The eight isolated strains were tested for their ability to degrade mixtures of hydrocarbons. Only two strains degraded paraffins at 5°C after six weeks. For the other strains the lag phase at 5°C seemed to be more than six weeks in experiments with monocultures.

BIOLOGICAL INVESTIGATIONS

Zooplankton and Fish

Several samples of zooplankton were collected in the vicinity of the spill and the species composition and abundance were analysed. The copepods were the dominant group in the plankton. One of the largest known calanoids, *Calanus hyperboreus*, occurring primarily in arctic waters, was the dominant species in the samples. *Calanus glacialis* and *Calanus finmarchicus* were also common. In samples collected with a small mesh size (0.333 mm), the smaller copepod *Pseudocalanus minutus* was one of the dominant species. Neuston samples taken in the vicinity of the spill were clearly dominated by *Parathemisto libellula*. The plankton samples were collected at different times of the day. Acquisition of samples at varying times during the day, combined with the known diurnal migration of plankton, made comparisons of samples from one location to the next uncertain.

The plankton samples were examined for the presence of oil either ingested or externally adhering to the cuticle.

The highest occurrence of copepods with oil in the alimentary tracts was found in a sample collected at the spill site eight days after the spill: 4% of the copepods there were found with ingested oil.

Figure 5. Parathemisto libellula; oil present in alimentary tract.

The amphipod P.libellula was found to have ingested oil in two samples, but only with a frequency of 2.5 and 0.8 percent.

The frequency of oil uptake in the gut was lower than reported at the ARGO MERCHANT spill (Maurer, 1977). These, samples in which oil was collected in the net together with plankton did not show a higher percentage of plankton with oil ingested. The size of the oil particles in the water column may be a factor influencing the amount of oil ingested by zooplankton, in that particles were to large to be ingested. If large particles were ingested by zooplankton these particles might have caused a blockage in the gut, which could have a fatal effect on individuals. These individuals may have sunk and were therefore not taken in the samples, resulting in an apparently low occurrence of oil ingestion compared to other observations.

Samples of copepods, amphipods and pteropods were analysed chemically for hydrocarbons. Small amounts of petroleum hydrocarbons were found in all groups, with the largest amount in copepods, and the smallest in pteropods. This may have been due to the higher lipid content in the copepods than in the pteropods. It should be noted that a reference sample from what must have been an unpolluted area also showed the presence of petroleum hydrocarbons, indicating that part of the petroleum hydrocarbons observed may have been introduced through contamination during sampling or analysis.

Very few fish were found in the spill area. Polar cod was analysed for petroleum hydrocarbons. Only a small amount of petroleum was detected, again possibly due to contamination from the sampling.

Seabirds and Marine Mammals

Very few birds were observed in the affected area. Apart from a few flocks of little auks (Poltus alle) and kittiwakes (Rissa tridactyla) only single birds, such as gulls, guillemots and fulmars, were observed. Some of the birds were seen swimming on areas of surface sheen, but oiled or dead birds were not observed. The stomach contents in a single fulmar taken in the affected area showed no signs of petroleum hydrocarbons. The low bird counts observed is not considered to have been a result of the spill because similar observations were made in adjacent unaffected areas.

Melville Bay is supposed to be an important breeding area for ringed seal (Pusa hispida). In the period 12-20 August, 43 ringed seals and 11 other seals were observed. No oiled seals were seen by the scientific parties, and the behavior of seals that were encountered seemed quite normal. More seals were expected in the area than were observed. The small number may have been due to the lack of sea ice in the area affected by the spill. (The ringed seal is known to occur mainly near sea ice.)

One month after the spill, 16 ringed seals with oiled skins were reported, and the oil from 12 ringed seals was analysed to determine whether the oil was derived from the POTOMAC spill. All the seals were contaminated on their backs. The oil from two seals caught shortly after the spill was very similar to the oil samples collected from the water surface, and it seems that the hydrocarbons isolated from the seals originated from the POTOMAC spill.

The other seals, caught 2-5 months after the spill, showed differences in the hydrocarbon composition, but the differences for some seals may have been due to biodegradation of the oil on the seals' skins, and the petroleum hydrocarbons might thus have originated from POTOMAC. For other seals it was not possible to determine whether the remaining hydrocarbons originated from the POTOMAC or from another spill.

SUMMARY

Fifty to one hundred percent of the compounds with vapor pressures equal to or greater than n-alkanes up to C_{17} of the oil from the POTOMAC evaporated over a period of two weeks. Some oil was lost to the water column, and the residue sank in 1000 m of water. No microbial degradation of oil was observed within four weeks. Oil was ingested by zooplankton, and was found on some seals. The spilled oil significantly contributed to the pollution of Melville Bay, which normally has very low petroleum hydrocarbon content in the surface water. This incident will probably have no lasting effect on the ecology of the water column; however, the 225 tons oil which sank to the bottom will remain there indefinitely.

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EFFECTS OF AN OIL SPILL ON SALT MARSHES AT HARBOR ISLAND, TEXAS. I. BIOLOGY

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ABSTRACT

On October 13, 1976, an American Petrofina Company pipeline ruptured, dumping about 377 barrels of crude oil into the cordgrass (*Spartina alterniflora*) and black mangrove (*Avicennia germinans*) marshes at Harbor Island in Redfish Bay near Port Aransas, Texas. A biological and chemical survey was begun the day following the spill. A single study site (4 stations ranging from above mean high tide to below mean low tide) was selected to monitor the benthos. Surveys of marsh vegetation were made on periodic trips to the area. Various types of clean-up procedures (including no cleanup of some areas) and different concentrations of oil coverage were monitored.

INTRODUCTION

Oil spills have received too little study due to the difficulty of prior planning, lack of baseline data, and little or no control over the oil. One of the most thorough studies available is of the West Falmouth, Massachusetts oil spill by Sanders *et al*. (1972) and Blumer and Sass (1972). Effects of oil spills on Gulf coast marshes have been minimally documented. Lytle (1975) found acute short-term (six weeks) effects but relatively minor long-term effects of a controlled artificial spill in a Mississippi marsh.

Early on October 13, 1976, an American Petrofina Company pipeline ruptured about two km from the oil storage "tank farm" on Harbor Island. The ruptured line released about 377 barrels of crude oil into the Harbor Island area along the Aransas Channel (Fig. 1). An easterly wind and an incoming tide moved most of the oil into the cordgrass (*Spartina alterniflora*) and black mangrove (*Avicennia germinans*) marsh in the southeast portion of Redfish Bay. Cleanup operations, headed by the Corpus Christi Area Oil Spill Control Association, began the morning of

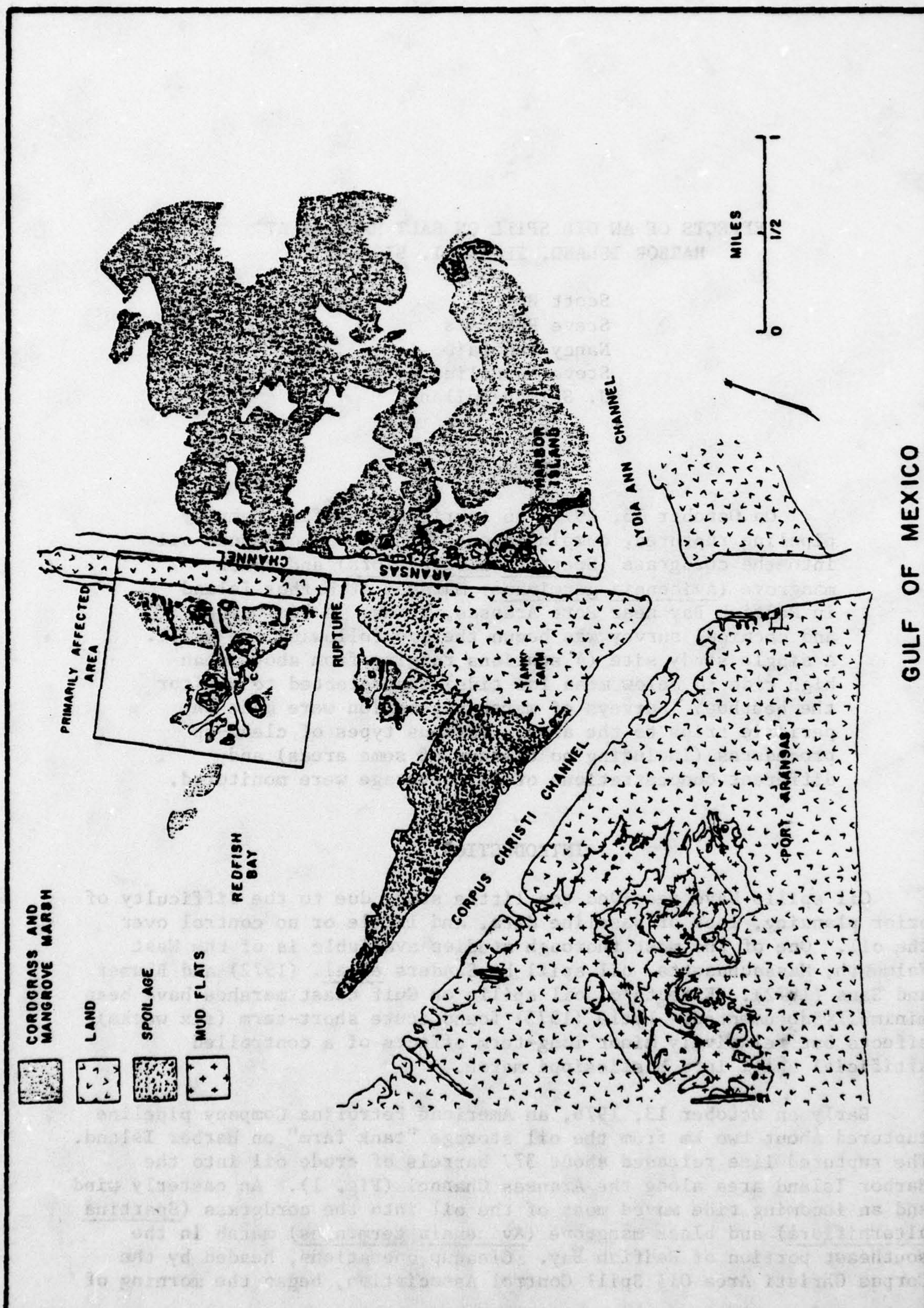

Figure 1. Area influenced by Harbor Island oil spill.

the 13th and were completed the afternoon of the 14th and reportedly recovered 80 to 85% of the oil.

Cleanup was accomplished primarily by soaking up floating oil with absorbent pads and scooping up oil-covered sand and mud from unvegetated shorelines. Some of the pads were removed from the area. Others were piled on heavily oiled shorelines and burned. In one area, this resulted in burning approximately 1000 m^2 of oiled and unoiled cordgrass and mangrove. Clipping of primarily emergent *Spartina* was also done in a few heavily oiled areas. One area of heavily oiled *Spartina* received no cleanup.

METHODS

Three lines of investigation were followed to examine the effects of the spill:

1) Periodic observations were made in the area to document the extent of the oil coverage and to follow the effects of the oil on the vegetation. Photographs were taken on each visit to supplement visual observations in the area.

2) A single site was selected to investigate the effects of the oil on interstitial invertebrates, primarily polychaete worms, molluscs, and crustaceans. Five sampling stations were established, ranging from below mean low tide to above mean high tide. Two 220 cm^3 core samples were taken at each station, 1 day, 8 days, 1 month, and 6 months following the spill.

3) Chemical analysis of the oil using gas chromatography and mass spectrophotometry was used to identify markers which can be employed to trace the fate of the oil through the sediments and through plant and animal tissue. Sediment, plant, and animal samples were taken periodically after the spill to investigate the uptake of oil, primarily in oysters, *Crassostrea virginica*, and cordgrass, *Spartina alterniflora*.

The results of the chemical investigations will be reported in a separate paper. This report gives an account of the visual observations of the movement and fate of the oil over the affected area (Fig. 1) and the results of the benthic invertebrate analysis.

RESULTS

Field Observations

One day post spill On 14 October, the day following the spill, a light film of oil was widespread over the southeast portion of Redfish Bay and a solid film of light oil covered large areas of the Corpus Christi Channel and Redfish Bay. This oil moved out the channel with tidal flow, and oil slicks were seen as far as six miles offshore.

Most of the lost oil moved into the *Spartina* and mangrove marsh

area in the west portion of Harbor Island. An east wind pushed the crude into the coves and vegetated shorelines of the marsh. Concentrations of oil were much greater on the windward shores and coves than on the leeward sides. The oil was carried further up into the marsh by a relatively high tide which occurred within 24 hours after the spill. These heavy concentrations were the source of a thin surface film which covered most of the open water in the marsh, especially on ebb tides.

In one area of heavy oil concentration (A, Fig. 1), the Corpus Christi Area Oil Spill Control Association burned the existing oil plus three piles of absorbent pads which were saturated with oil. The burned area had been covered with Spartina, which grew from below mean low tide to above mean high tide, and a few scattered mangroves. The crude oil did not burn completely and a very heavy tar was left after the lighter portions burned off. This heavy tar covered the unburned stems of the Spartina, especially those growing in the water, and collected in a heavy mass of tar floating at the water's edge. Another area of very heavy concentration (C, Fig. 1) was along a shoreline vegetated with mangrove. All the aerial roots and the lower stems and leaves of the mangroves were covered with thick oil. A third heavy concentration of oil (B, Fig. 1) was found in a 40 ft by 20 ft stand of Spartina growing on a low island which was exposed only on very low tide. Thick oil covered the water in the Spartina "island" and made a thick covering on the plants from their bases up to one foot high on the stems.

Eight days post-spill Eight days after the spill, the open water in Redfish Bay and the Corpus Christi Ship Channel was free of oil slicks. Within the Harbor Island marsh, the heavy concentrations of oil had dispersed from most of the water and exposed substrate along the shoreline, leaving a thick layer of oil on the stems, leaves and aerial roots of the Spartina and mangrove. In the areas of heaviest concentration, light oil continued to escape from the thick crude and formed slicks on the adjacent open water. In these areas heavy crude still floated on isolated pockets of water and lay exposed on intertidal substrates. Most of the crude was trapped in the vegetation and could not float free.

During October 22-25 the Oil Spill Control Association renewed their cleanup efforts. They removed most of the very heavy concentrations of oil from area A which by this time had thickened to a tar consistency, and clipped and removed some of the heavily-coated Spartina. Spartina was also clipped in a small, heavily oiled pond near area A. Extensive damage was done to the sediment structure and Spartina root systems by the workmen moving through the pond. By this time most of the oil had adhered to the vegetation or was incorporated into intertidal substrates and the measures necessary to remove all the oil would have been very destructive to the area.

Thirty days post-spill One month following the spill, oil was still evident at all the heavily and moderately affected areas. In the lightly affected areas there was little evidence of the oil other than a few isolated spots of oil clinging to the Spartina or mangroves. There was no visual evidence of oil on the substrate. In the moderately affected areas, remnants of the oil were evident as dark lines in the Spartina

and mangrove which marked the height of the high tide on the days immediately following the spill. The oil still adhered to the Spartina stems and to the aerial roots of the mangrove but it appeared to have weathered sufficiently so that rubbing was necessary to get it on our skin. There was no obvious damage to the Spartina or mangrove in the moderately affected areas, but October-December is a time of general decline of all Spartina in this area and poor condition or even death would be difficult to detect. The intertidal substrate in the moderately affected areas had small amounts of oil trapped under the surface and in a few places oil was visible on the surface.

Oil was still present in great abundance in the heavily affected areas. Isolated intertidal pools within stands of Spartina and mangrove were covered with a thick layer of heavy oil and relatively unweathered oil covered the stems and leaves of the Spartina and the aerial roots, stems, leaves and seeds of the mangroves. The leaves and seeds of some mangroves, which had been heavily covered with oil, had withered or fallen off. The remainder of the affected plants, however, appeared in relatively good condition. Undisturbed intertidal substrates in these areas appeared free of oil but a heavy layer of oil was present about one cm below the substrate. Light pressure or digging in these muddy sediments revealed large amounts of oil trapped in the substrate.

One hundred eighty days post-spill Six months after the spill there were no visible signs of oil in the sediments or on the vegetation in the lightly and moderately affected areas. Only the heavily affected areas showed obvious signs of oil. The heavily oiled Spartina which had been burned was only moderately recovered. Recovery was poorest in the Spartina growing in standing water. In some parts of this stand there was no new growth and in the remainder, new growth was patchy and thin. Oil remained trapped in the sediments both above and below mean tide level. Contrary to this, the Spartina in area A, which had been clipped to the water line rather than burned showed relatively good recovery. The burned mangroves in area A were completely dead. No mangroves were sprouting in the burned areas whereas numerous young mangrove were sprouting in the immediately adjacent unburned area.

The effects of oil were still evident in the heavily oiled small pond near area A. In this area the vegetation had not been burned but some of the Spartina was clipped and removed. Clipped Spartina growing in the water showed little or no sign of new growth, whereas clipped Spartina growing above mean high tide showed relatively good recovery. This area suffered heavy mechanical damage to the substrate as a result of the cleanup operation and still had a disturbed appearance.

Unburned black mangrove showed no effect of the oil. Those plants which lost leaves due to heavy oiling had replaced them by the next growing season and all mangroves in the area appeared in good condition.

The most severe damage was in the heavily oiled Spartina "island" in area B where the heavy concentration of oil was not cleaned up. Most

of this Spartina was dead and showed no signs of new growth. The sediment still held large amounts of oil which floated to the surface and formed slicks when the sediment was disturbed.

Quantitative Results

Infauna Benthic samples were taken 2 days, 8 days, 1 month, and 6 months after the oil spill. Samples were analyzed for number and kinds of organisms, determined to lowest possible taxa.

Samples were composed primarily of polychaetes (82%), crustaceans (14%) and molluscs (3%). Total numbers of individuals of these three groups were lower in the two successive sample periods after the oil spill (2 days and 8 days post-spill) than in those taken 1 month and 6 months after the spill. Species richness (number of species) remained fairly consistent throughout the sample periods (21, 18, 23 and 19 species, respectively).

Changes in the benthic samples with time were due to relative changes in the numbers of individuals of dominant species. The polychaete, Capitella capitata, comprised 57% and 53% of the total number of polychaetes in the samples taken 2 days and 8 days post-spill, respectively, and only 28% and 30% in the 1-month and 6-month samples, respectively. Laeonereis culveri followed the same pattern (12%, 14%, 9%, and 3% of the total number of polychaetes) in the four successive sample periods. Streblospio benedicti, Haploscoloplos sp. and Fabricia sp., on the other hand, comprised lower percentages of the total number of polychaetes immediately following the spill, but increased in the 1 month and 6 month post-spill samples.

Numbers of nematodes were consistent in the first three sample periods (15, 14 and 17, respectively) but rose sharply in the 6-month post-spill sample (151 individuals).

It was noted during workup of benthic samples that the condition of the organisms in the samples taken 2 days and 8 days after the spill was poor and that the specimens appeared to be partially decomposed.

No data were available on the structure of the benthic community immediately prior to the oil spill.

Spartina Standing crop estimates were made in three areas chosen to represent oiled and burned, unoiled and burned, and unoiled and unburned Spartina stands. All sites were at approximately the same height above mean sea level. Estimates were made by clipping all standing material in two 0.25 m^2 plots in each of the three areas. Living material was removed, dried, and weighed (Table 1). The t-test statistic for two sample means (Elliott, 1977) was used to test all possible pairs of means (Table 2). The oiled and burned area was significantly ($p = .05$) different from both unoiled areas, either burned or unburned (Table 2).

Table 1. Dry weights of living Spartina in three sample plots.

		Sample Plots		
		1	2	3
		Unoiled-unburned	Unoiled-burned	Oiled-burned
Replicate	1	182 g	147 g	102 g
	2	151 g	154 g	93 g
Mean		166 g	150 g	97 g

Table 2. t-test for all possible pairs of means

Paired Means	t
1 & 2	1.01
1 & 3	4.31*
2 & 3	9.30*

* Significant at the 95% level

DISCUSSION

The long-term effects of the oil spill were minimal in most of the affected areas. Only in those areas with heavy concentrations of oil were effects obvious through the first growing season. In these areas, growth (or recovery) of Spartina was much reduced compared to more lightly affected areas. Those areas where the Spartina was burned or clipped showed only slightly better recovery than non-cleaned areas. Baker (1970) found similar results with Spartina townsendii in England.

It appears that Spartina, not growing in standing water, recovers rapidly from burning, even in areas where there is a light covering of oil. Heavily oiled Spartina, however, responds poorly to burning. Heavy concentrations of tar remained on the stems of emergent Spartina burned to the water level and these showed no recovery. Heavily oiled and burned Spartina, not in standing water, had significantly lower biomass than non-oiled and burned or unburned stands. Mangrove is completely intolerant of burning but appeared relatively tolerant to even heavy oiling.

Clipping proved to be a relatively successful method of removing oil and oiled Spartina but in some cases the physical damage to the root systems and sediment structure may have been more damaging than the oil. Extreme care must be taken in any cleaning procedure to avoid trampling the plants.

An area of particular interest is the heavily oiled Spartina "island" which was not cleaned. In this area, as in all other unburned, unclipped areas, the detrimental effect of the oil was not apparent

until a few months after the spill. Baker (1970) presents evidence that oiling outside the growing season is not damaging but Lytle (1975) saw evidence of damage to Spartina within three days of an artificial spill in July, in the middle of the growing season. Our results indicate that heavy oiling at the end of the growing season was manifested in the next growing season. Hampson and Moul (1977) reported almost no recovery of Spartina even 3 years after a heavy spill of No. 2 fuel oil in Buzzards Bay in October. Heavy oiling of Spartina in any season is apparently lethal.

A near total kill of infaunal organisms, such as seen at the West Falmouth Oil Spill (Sanders et al., 1972), was not seen at our study site. However, the lower infaunal density immediately following the spill and the relatively high abundance of Capitella capitata (generally considered an opportunistic species (Grassle and Grassle, 1974), and indicative of pollution) collected soon after the spill indicated some short-term damage to the infauna.

The damage resulting from this relatively small spill (< 400 bbls) in the Spartina-mangrove salt marsh indicates the disastrous potential from a large spill which could occur in this area due to increasing oil exploration and transportation on the Texas Gulf coast. From this study it is obvious that prevention is the best treatment.

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HIGHLIGHTS REGARDING THE IMPACTS OF OTHER PERTINENT OIL SPILLS (SESSION II)

Chairman: PAUL LEFCOURT
U.S. Environmental Protection Agency

PHYSICAL ASPECTS OF THE OIL SPILL FROM THE SUPERTANKER 'METULA'

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PHYSICAL ASPECTS OF THE OIL SPILL FROM THE SUPERTANKER 'METULA'

The oil spill from the supertanker METULA, the world's second largest at the time, serves as an important laboratory since cleanup operations were not carried out.

The persistence of the oil in and under beach sands, on cobbled beach surfaces, in the intertidal zone and in the estuaries and marshes has helped us make recommendations for control of later spills.

History of the Spill

The supertanker METULA ran aground on satellite patch shoals just inside the First Narrows of the Strait of Magellan during the late evening of August 9, 1974. The METULA had been proceeding from Ras Tenura in Saudi Arabia on the Persian Gulf to Quintero Bay, Chile with a load of over 196,000 tons of light Arabian crude oil for ENAP, the Chilean National Oil Company. The METULA, with its 1,067-foot length, 62-foot draft, and 206,000-ton deadweight capacity, was the first ship of the VLCC (Very Large Crude Carrier) class or supertanker of over 200,000 deadweight tons to be involved in a major oil spill of this size. The cause of the grounding will undoubtedly someday be reported in detail. It will suffice to say that it revolves around the severe tide and current conditions of the First Narrows area of the Strait, the cold blustery winds blowing toward the bridge of the tanker during the long winter nights of the high latitudes, the difficulty of navigating this large a ship with a minimum of navigation aids, and various human factors. It is really adequate to say that the METULA for some reason cut a corner too sharp and hit the curb. In this case, the curb was a 40-foot shoal which was struck by a 60-foot draft ship.

The general location of the grounding site is indicated in Figure 1.

On the second day after the grounding, the METULA swung to starboard and holed and flooded its engine room compartments. The need of external pumping systems to remove the remaining cargo became imperative. The U.S. Coast Guard, responding to a request for assistance by the Chilean Government, played a major role in limiting the loss of the oil from the METULA.

This assistance primarily involved their use of air deliverable ADAPTS pumping systems to aid the salvage operations by transferring oil, offloading oil and pumping water overboard during the refloating attempt. The METULA was eventually refloated on September 25, 1974, and eventually left the Strait of Magellan under tow to Isla Grande near Rio de Janeiro and was ultimately scrapped.

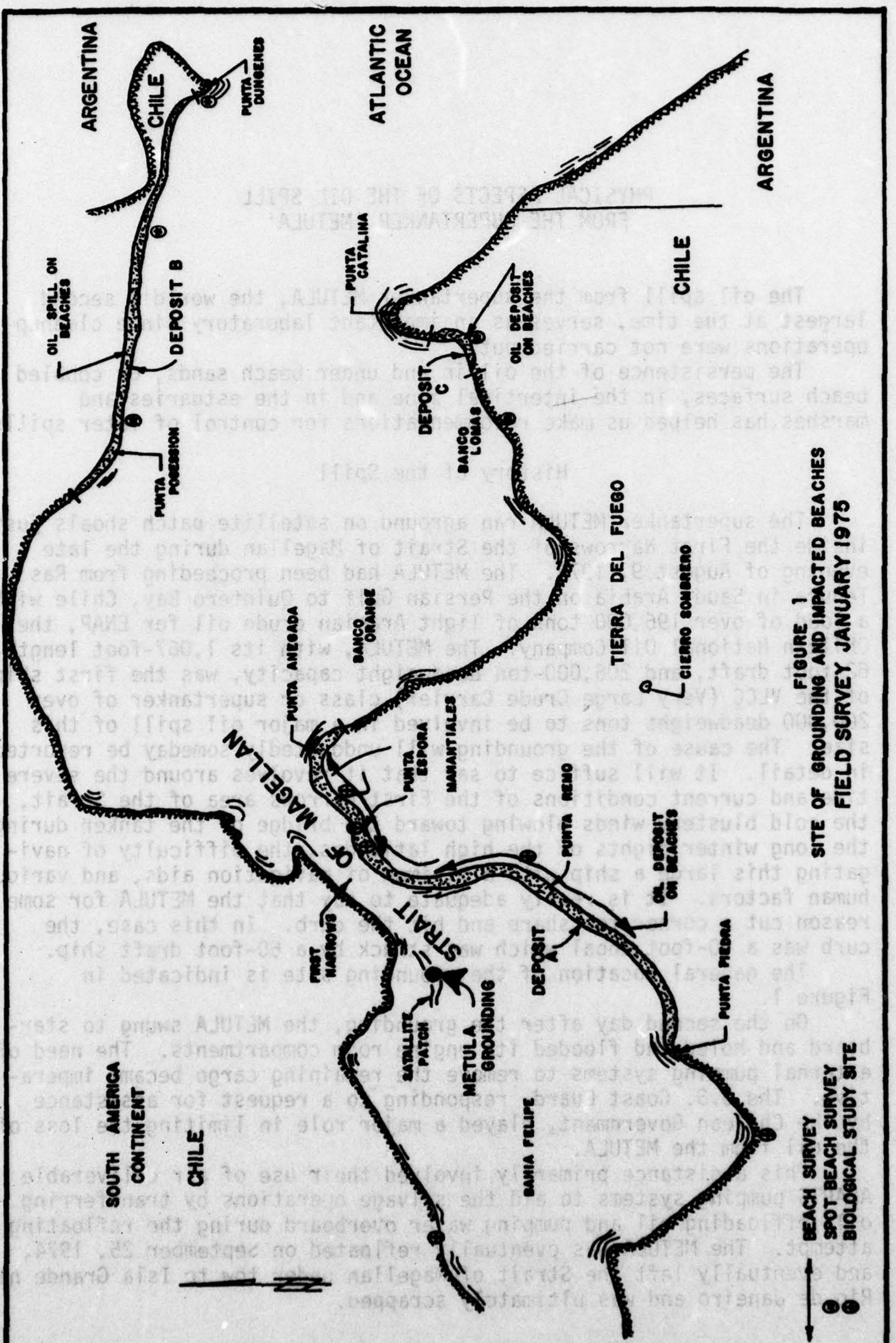

FIGURE 1
SITE OF GROUNDING AND IMPACTED BEACHES
FIELD SURVEY JANUARY 1975

Initial Deposition, Subsequent Spreading, Ultimate Fate and Impact of the Oil Spilled from the METULA

The initial spill was reported to be 6,000 tons. Subsequent spills continued with the largest being 20,000 tons on or about August 19, until the total reported spill quantity of 51,500 tons of crude oil and approximately 2,000 tons of Bunker C fuel oil was reached. The oil would initially spread over large areas of Bahia Felipe and Bahia Gregario to the west of the First Narrows and to a lesser degree to Bahia Posession to the east. The intial dispersion was predominantly by gravity and surface tension spreading superimposed on the local currents, which were as high as ten knots from spring tides which ranged on the order of 20 feet. Northwesterly winds on the order of 30 to 50 knots drove the floating oil ashore usually within a few hours after release, primarily on the southern shore of the First Narrows and on the southern shore of Bahia Felipe.

The author's involvement with the METULA spill began on August 23, 1974 when he was requested by the U.S. Coast Guard to accompany their contingency as Science Advisor with the role of technical assistance on cleanup operations if any, evaluating future equipment needs for high speed current oil recovery and to evaluate the fate and effect of the spilled oil with regard to its importance to the United States as it enters the supertanker era, particularly in colder climates. Since cleanup of this spill was not undertaken, the author focused his attention on learning the fate and effect of the oil.[2]

In this role, he was greatly aided by staff members of the Instituto de la Patagonia, a research institute located at Punta Arenas on the Strait of Magellan and an IMCO Consultant.

With help from the Chilean Navy and ENAP, the combined team spent almost a week on the field and surveyed the 25 miles of coastline which was most heavily impacted and portions of the two small tidal estuaries which enter the Strait on the south shore of the Narrows.

The author returned to the scene in January 1975 as the coordinator of a U.S. Team comprised of representatives of NOAA, EPA, and the U.S. Coast Guard.

The primary purpose of the second trip was to determine the fate of the oil over the intervening five month period since the spill and to look in greater detail into the impact of the spill on the marine life in the beach and intertidal zone.

Additional trips were made in January of 1976, 1977 and 1978 to further evaluate the weathering of the oil and the physical changes in the impacted systems.

The initial survey was of necessity brief because of the short days, cold and winds (5°C and 40-50 knots) and logistical difficulties because of the remoteness of the area. The study took place from August 29 to September 3, 1974 after most of the oil had been spilled, but before the ship had been refloated.

Beach Impact

The team found that the oil on the beach was in two different forms; a dark brown mousse material which had been deposited high on the beach-front by previous spring high tides and winds and a lighter brown (milk chocolate) mousse which was suspended at the present high tide mark,

floating at the water's edge and stuck to the rocks and bottom in the intertidal area.

The dark mousse contained 5-10 percent water by weight and included seaweed, sand, small organisms and other materials.

The lighter mousse contained 25-30 percent water by weight and also included sand, seaweed and small organisms as constituents.

The darker mousse typically covered from 6 to 15 meters of flat area at the top of the beach with oil from 5 to 10 centimeters thick.

The light brown mousse would typically cover from 15 to 60 meters of beach in depths from one centimeter thick to 5 centimeters. This material would also be found in and around the rocky areas exposed in the Intertidal Zone when the tide would go out. The rocks in these flat areas at the bottom of the beach would typically be rounded boulders of from four to eight inches in diameter and in many cases, appeared to have a milk chocolate frosting on the top (much like cupcakes) from the deposition of the oil.

The fast transport time of the oil to shore coupled with the cold air and water temperatures undoubtedly resulted in less loss of volatile materials to the air and water column than would usually occur.

The inventory conducted on the beach on August 30 and 31 led the team to believe that between 75-90 percent of the total oil spilled was ashored on a 40 mile stretch of Tierra del Fuego.

Figure 1 shows the location of the spill and the beaches which were observed to be heavily covered with oil during the initial field study.

Strong southwesterly winds on September 1 stripped some oil from these beaches, particularly in the exposed Narrows area and redeposited the oil on the northshore east of Punta Posession and later following another wind shift on Banco Lomas west of Punta Catalina. This redistribution was verified later by aerial survey. Thus, by early September, some 75-80 miles of coastline was impacted to varying degrees.

During the follow-up trip in January, the team was particularly concerned with what had happened to the oil on the beaches. This and subsequent studies by a University of South Carolina team indicated that between 125 and 150 miles of beach were visibly impacted.[1,3,5]

On the southshore of Bahia Felipe, it was found that the oil previously stranded at the top of the beachline was still exposed.

The stranded deposit varied from a couple of meters wide and approximately one centimeter thick at the southernmost point in Bahia Felipe to deposits 15 meters wide and over 15 centimeters in thickness near the center of the Bahia Felipe southern coastline. In addition, it was found that the oil below the stranded exposed layer had become incorporated in the beach sand as a mixture of sand, rock and light brown mousse, often covered with clean sand and rock.

In many places, this deposition of mousse, sand and rock was over 15 centimeters deep and from 15 to 22 meters wide.

Oil was observed almost everywhere under the upper beach sand, if one looked hard enough. The team soon learned to locate the thicker deposits by the quicksand-like condition created when the mousse coated and lubricated the rocks and sand.

The heaviest deposits were located in the eastern half of the southshore of the First Narrows in the Puerto Espora area. Here much of the beach surface remained coated with oil and in many cases, the mousse was well mixed with the upper three or four inches of the intertidal bottom.

The area near the ferry at Puerto Espora has exposed tidal flats over 600 meters wide which, when the tide is out, look like a paved airport ramp over 400 meters wide and three and a half kilometers long. The name moussecrete was coined for the mixture of mousse, sand, gravel, mussels, etc. which pave the intertidal areas. This area was much heavier coated in January 1975 than in September.

In January 1976 the survey of locations on the south shore of Bahia Felipe from the site of the former Hotel Bahia Felipe to Punta Piedra showed substantial weathering of the remaining oil which included only occasional patches of crusted oil above the high tide line. The crusted area was rapidly being broken up and dispersed or covered by sand and gravel.

The southeastern coastline of Bahia Felipe from Punta Remo to near Punta Baxa still showed major signs of contamination in 1978. A blackened zone ranging from 3 to 15 meters wide bands the top of the beach zone. This zone now consisted of a dark tarry crust on top of 5 or more centimeters of oiled sand. Fresh-looking mousse is found on, in and under kelp and other detritus. For a distance of from 10 meters to 15 meters seaward from the blackened band, oily sand or mousse and sand is occasionally under surface beach sand. In 1977 this ranged from 5 to 30 centimeters in thickness and was covered by from 5 to 15 centimeters of either clean or dirty (slightly oiled) beach sand.

Within the broad rocky intertidal zone exposed seaward of the sand beach slope, occasional patches of rocks are found at the higher elevations which are cemented with patches of black surfaced asphalt. Mousse is found under the black surface and around the edges of many rocks that are turned over.

At one location dozens of black tar balls from 3 centimeters to 5 centimeters in diameter consisting of weathered oil, shell, and sand were found.

A stretch of beach in front of the cliffs to the north of Punta Baxa showed a thin crust of oil from 1 to 3 meters wide over about half of the length but none at the other locations. There is considerable oiled seaweed and other detritus at the top of the beach. Several large rocks up to 1 meter in width and 50 centimeters high were covered with a heavy black tar coating on the top and seaward sides.

Mousse was found under and around the edges of many (i.e. 10%) of the rocks in the first 10 meters of rocks seaward from the base of the sand beach slope. Some oiled rocks appeared to be covered by the bottom slope of the building beaches.

A survey of the shore of the Narrows westward from Punta Espora showed almost no visible evidence of petroleum at the top of the beach and in the upper beach sands.

The broad arc called the Bahia Azul Shoreline (i.e. from Punta Espora to the West Estuary Entrance) retains some visual signs of petroleum. The layer of shell and flat rocks at the top of the beach line which was noted previously is still evident. The oil has weathered and about one-third of the front of the deposits have been eroded by high tide. Many tar lumps from 1/2 centimeter to 8 centimeters in diameter by 1 to 2 centimeters thick are found in the beach sands.

Beginning near the ferry landing and running for some 2 kilometers eastward is a band of moussecrete some 15 to 30 meters wide which has hardened like a road or sidewalk. In some places the deposit is covered by fresh pebbles, but they can be easily swept away to see the hard surface.

The lower intertidal zone of the Puerto Espora area looks even now more like a paved airport ramp than in January of 1975. The intertidal zone ranges from 500 to 600 meters wide and about 3 to 4 kilometers long. Of the 400 meter wide lower intertidal zone measured seaward from the base of the beach slope, approximately 60 percent of the western third, 95 percent of the middle third and 80 percent of the eastern third, are covered with a black asphalt-like surface. Some erosion of this area was evident in 1978. In places near the beach, the moussecrete is almost 12" thick.

The western third includes the area of the former ferry landing, the West Estuary outlet and some clay areas.

The asphalt has blackened in all but the lowest intertidal areas and generally averages from 5 to 10 centimeters in thickness with some exposed areas to 15 centimeters noted. An especially heavy area east of the East Estuary entrance has large areas which have mousse mixed with sand for over 30 centimeters in depth.

The seaward 100 meter wide stretch of the intertidal zone exposed at the spring low tide is generally not coated with oil and is rich in algae and some mussels.

The beach zone in this area is clean except for a layer of black-sandy asphalt at the top of the beach and considerable oiled detritus. The wash of the receding waves has eroded the first few feet of the paved material at the base of the slope. In time, this erosion may progress seaward at a slow rate.

There is beginning to be a substantial growth of attached algae on the surface of the hardening pavemented areas. The algae is heaviest in the lower elevations normally covered with water.

East and West Estuaries

Two small estuaries located on the south shore of the First Narrows were heavily impacted by the spill. The East Estuary at the Narrows was situated with regard to wind and nearshore currents so that it was oiled to the end of the smallest channel in the estuary--a distance of about two miles inland.

Even after five months, the upper reaches of the estuary had 15-20 centimeters of oil floating in the channels. The banks near the mouth had mousse mixtures to 30 centimeters deep, flat areas between channels often had pools of oil standing 10 centimeters deep and the bottom of the main channel near the mouth has a 2 to 5 centimeter oil-coated bottom.

The West Estuary was not as heavily coated, but still had as heavy oil deposits in January 1975 as in the previous September.

In January 1978 the East Estuary remained the desolate wasteland observed on the earlier trips. Banks and flat areas were still clogged and covered with soft oil deposits. The only change was in the inland channels which previously had been completely filled with oil. Most of this oil had been moved out of the channels by high tides and into flats between the channels. The deposits in the flat areas are soft and soupy with a black film, but no noticeable crusting or hardening.

The West Estuary remained visibly much the same as in both the previous trips except the surface of the oil deposits had blackened, hardened, and become thinner by evaporations and seeping further into the sediments. There is still much mousse on the surface. This is undoubtedly because little sand enters the estuary to mix with the oil. It is still soft and slippery when warm.

Further inland is a long channel which is solidly covered from low to high tide line with an "asphalt paved" area. The thickness is approximately 5 centimeters in this stretch. Similar areas, but not as consistent were observed on the north shore.

Waterfowl and Marine Life

The initial wildlife concern was for marine waterfowl known to be in the area. The initial survey turned up over 200 dead or dying birds. Cormorants and penguins predominated with a smattering of gulls, terns, ducks, albatross and other species being found.

Cormorants were most heavily affected. The three species in the area were rock cormorant, blue-eyed cormorant and the king cormorant. Most of the cormorants found in the oiled beach zone were so heavily oiled that species identification was not possible. Cormorants were particularly susceptible to the oil since they dive into the water for their food and may come in contact with the oil while diving or surfacing. Cormorants also came in contact with the oil on the beach by landing or walking on and in the oil.

Penguins, although second in mortality to the cormorants, were the focus of the greatest concern by the scientistic community.

Oil affects penguins by interfering with their flotation ability and insulation. About 50 dead or dying penguins were found on shore during the initial survey. Both the Magellanic Penguin, sometimes referred to as the Jackass Penguin, and the Rock Hopper Penguin, which are common to the area, were found.

The main concern in September of 1974, however, was for the pending penguin migration from the Atlantic Ocean to Rookery Islands in the central Strait of Magellan, two of which (Islad Magdalena and Isla Marta) comprise the Los Pinguinos Chilean National Park.

This migration which ultimately took place in middle September and which involved tens of thousands of penguins could have been drastically harmed if the surface of the water had been heavily oiled during their passage.

Fortunately, by the time of the migration, the ship's leaking had been minimized and most of the spilled oil was either pinned on the shore or naturally stabilized on the beaches or in the estuaries.

Only casual examination was made of the organisms in the lower Intertidal Zone along the impacted area during the August-September trip.

The January trip coincided with the spring low tides and it was possible to reach the lower Intertidal Zone which was uncovered. Relatively heavy mussel beds were located in a number of rocky areas near the low water mark. Indeed the area had been much richer in biological life than originally believed.

It was noted that marine life on the relatively uncontaminated northshore was substantially more dense in terms of mussels, limpets, crustacea, worms and other organisms than the impacted south shore. Although many adult mussels were surviving on the lower zones of the impacted beaches, there was a noted lack of juvenile mussels, juvenile and adult limpets and a complete lack of crustacea.

Summary

The oil from the METULA spill is disappearing at varying rates at different locations on Tierra del Fuego.

The exposed coastline is hiding or dissipating the oil into the sea by wave turbulence, blowing sand, and deeper penetration into the beach. Beach detritus such as oiled kelp and kelp holdfasts, lumber and trash will probably be evidence of the spill for the longest time.

In the estuaries and protected areas, the rate of change is much slower and confined to the aging and hardening of the oil by air exposure and deeper penetration into the sediments. Removal is evident only where greatest energy is exerted, i.e., high velocity flowing channels and exposed beach top areas. Some fossilized birds are still in evidence. Salicornia is beginning to recover and grow through some oil deposits where previous stalks were present.

The magnitude of the METULA spill coupled with the absence of any cleanup activity has made the spill serve a valuable role as a test system to observe the recovery from a major spill.

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BIOLOGICAL STUDIES OF THE METULA OIL SPILL

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ABSTRACT

A brief review is presented of biological studies conducted after the *Metula* oil spill. The relationship between the distribution and abundance of intertidal invertebrate species and the petroleum in the intertidal quadrats is discussed. The data suggest a continued impact of petroleum in quadrats remaining heavily oiled and recovery of invertebrates in other quadrats where petroleum is being gradually lost. The data are difficult to interpret due to other patterns of abiotic and biotic variability in the area.

INTRODUCTION

On August 9, 1974 the *Metula* grounded at Satellite Patch just west of the First Narrows in the Straits of Magellan. The vessel was not refloated until 25 September, 1974. 50,000 to 56,000 tons of oil were spilled during this period (Hann 1974,1975; Baker 1974; Baker et al., 1975). Most of this was light Arabian crude oil but 3,000 to 4,000 tons of Bunker C were lost during the last few days of the grounding. This light Arabian crude oil was similar to the Kuwait crude oil used as an API reference oil (Warner 1975) and to that spilled from the *Torrey Canyon*.

The distribution of oil on the surface of the ocean and in the intertidal zone has been documented periodically during and after the oil spillage (August 1974 by Hann 1974; September-October 1974 by Baker 1974; January-February 1975 by Baker et al. 1975, Hann 1975, and Gunnerson and Peter 1976; January 1976 by Hann 1977; January 1977 and January 1978 by Hann 1978). Most of the stranded oil came ashore between Punta Remo and Punta Anegado (Fig. 1). The highest concentrations of oil were observed in the Puerto Espora area. Isolated

patches of oil were recorded in the high intertidal areas as far east as Bahia San Felipe.

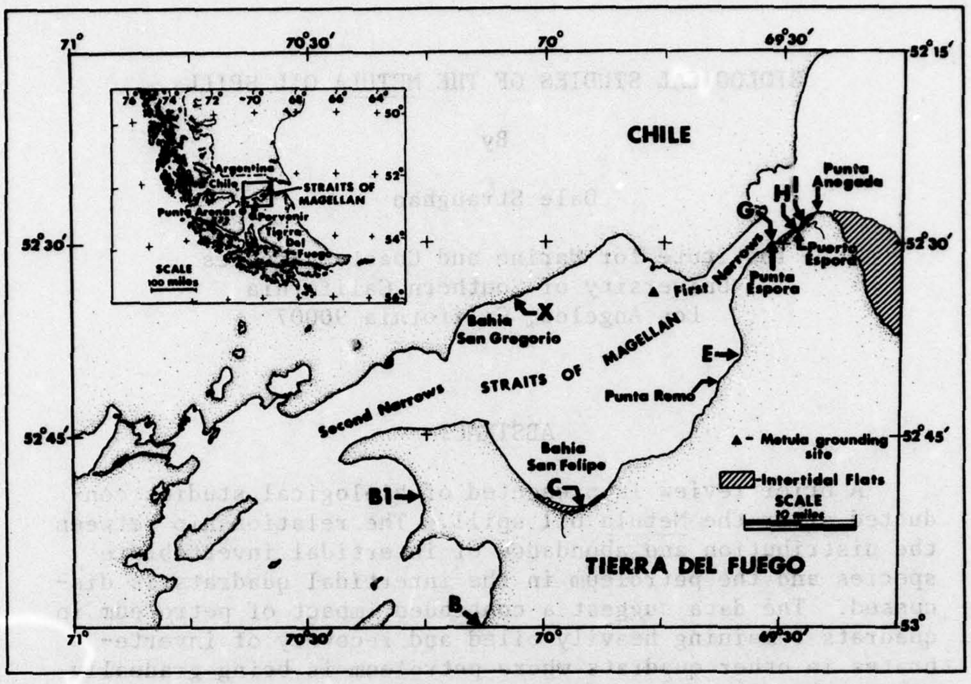

Figure 1. Map of the Straits of Magellan showing intertidal collecting sites.

Biological studies have been undertaken by a number of personnel. Baker (1974) and Baker et al. (1975) conducted an overall biological assessment of the situation in September-October 1974 and in January-February 1975. In 1975 biological surveys were conducted in the intertidal zone (Straughan 1977). In addition, bacteriological samples were collected for Dr. Rita Colwell. Subsequently, ongoing studies have been conducted by personell at the Institute de la Patagonia (Guzman 1976). Ecological surveys were also again conducted intertidally by Straughan in January 1977. A botanical survey was also conducted by NOAA in January 1977 (Emerick 1978).

The surveys by Baker which covered a large area both geographically and ecologically in a short period of time, virtually recorded bird mortalities as the only discernable impact. The importance of the figures of the dead birds is difficult to evaluate because, as Baker comments, it is unknown what relationship the total estimate has to the real mortality. Baker does not indicate whether her observations show a significant impact in either intertidal or <u>Macrocystis</u> beds but one is left with the distinct impression, that as with the bird population, Baker does not believe there will be a significant long term impact.

Straughan's studies in 1975 showed that large areas of the intertidal zone either lacked invertebrates or were sparsely populated and suggested that while these intertidal areas were probably never very densely populated, that some of this sparcity in biota was due to the oil spill.

The intertidal areas were resurveyed in January 1977 and hopefully they will be resurveyed again in January 1979. This oil spill is important in providing data on the impact of a large spill of this type of oil in a cold water environment when virtually no attempts were made to clean up the oil. In this case I think two men worked with hand tools and no chemicals for several days. The aim of these studies is to detect impact of the oil and recovery of these areas against a background natural variability.

THE INTERTIDAL SURVEY

The survey methods used in these ongoing studies are detailed in Straughan 1977. The basic approach is to measure chemical, physical, and biological parameters at the same location in space and time. These same techniques were employed in 1977 as in 1975.

The location of the sites studied is shown in Figure 1. These sites were originally selected based on preliminary surveys by Baker and Hann followed by ground reconnaissance of the site.

The surveys were conducted at the same sites in both years. Due to difficulties in relocating sites in these habitats, Site E, 1977 was a short distance along the beach from Site E, 1975 and quadrats 1,2,3,4 at Site G also differed by a matter of a few feet intertidally in the two years. However, abiotic parameters of both a chemical and physical nature as well as biotic parameters, are recorded at each quadrat. Since the analytical techniques used in the data analyses involve the relationship between the abiotic and biotic data for each quadrat using multiple discriminant analyses, these discrepancies in site location can be accounted for in the final data analyses.

Site A in the sheltered inlet at Porvenir, bore a surface green algal film in 1977. When this site was selected in 1975, this algal film was observed in large areas of the inlet and visually suggested that there may be organic enrichment of the area such as sewage pollution. In 1975, the quadrats were selected outside this algal area, but in 1977, this area of apparent organic enrichment had expanded to include quadrat A-1.

The field sampling techniques involved collection of ten replicates in each quadrat. The use of the information statistic ($1-r^2$) has shown that this is an adequate number of samples for the quadrat. In fact, over 90% of the information would have been obtained if only 6 replicates were collected. Therefore, the collection of 4 additional

replicates at each site added less than 10% to the total information. It is unlikely that there would be a statistically significant increase in information if more than 10 replicates were collected.

Table 1 lists the abiotic parameters that were measured on each survey. Details of the methodology for these measurements are provided in Straughan 1977. Note that several parameters measured in 1977 were not measured in 1975. These included sediment temperatures and Ohaus measurements for moisture and organics in the sediments. The reasons for this lack of data are related to the very heavy oil contamination of sediments which interfered with the operation of the equipment.

Table 1
Abiotic Parameters Recorded 1975, 1977

Abiotic Parameter	1975	1977
Temperature		
Air	+	+
Water	+	+
Sediment		+
Salinity	+	+
Intertidal Height	+	+
Sediment		
Grain Size	+	+
% Water	+	+
Ohaus Moisture Content		+
Ohaus Organic Content		+
Petroleum		
Visible Presence	+	+
C Cl_4 Extractable	+	+
Source	+	+

At this stage data analyses are incomplete because of the difficulties in ensuring that the sediment data from the two surveys are comparable. These problems are related both to the need to wash the samples heavily contaminated by petroleum and the difficulty in obtaining comparable data in areas where the sediments are unevenly distributed and range from cobbles down to silt. A final report will be presented to NOAA when these sediment analyses problems have been resolved. This paper will therefore emphasize the relationship between Metula oil and the distribution and abundance of invertebrates.

Interpretation of the data is complicated by warmer more saline waters in the area during the January 1977 survey than during the January 1975 survey. Salinities in 1977 were generally 2 to 5 parts per thousand higher than in 1975 and approximated to normal seawater levels (35°/oo). Water temperatures in 1975 ranged from 8°C to 10°C while in 1977 water temperatures ranged from 9.9 °C to 15.5°C with one record as high as 18.5°C in a marsh channel.

THE OIL

Chemical analyses of organisms and sediments were conducted by Dr. J.S. Warner of Battelle, Columbus. Briefly, the mussel samples were homogenized, saponified with aqueous NaOH, extracted with ether, fractionated by selica gel chromatography, and the resulting fractions analyzed by gas chromatography using high resolution glass capillary columns. The "aromatic hydrocarbon" fraction was cleaned up by high pressure liquid chromatography to remove interfering biogenic olefins prior to the GC analysis. The tar and sediment samples were extracted with carbon tetrachloride and the amount of extractable material was determined by both infrared analysis and gravimetric analysis. Gas chromatograms were obtained for each extract using a high resolution glass capillary column and using both a flame ionization detector and a sulphur specific flame photometric detector to determine the presence of petroleum and provide a qualitative comparison with Metula oil. These later data are summarized under the chemical analyses section of Table 2. The original data are provided in Straughan 1977 and the report to NOAA for the survey in 1977.

Note that the tar recorded in quadrats G-5 and X-1 gave a GC pattern that was indicative of a low-sulphur paraffin wax rather than a weathered Metula oil.

The visible presence of petroleum decreased at most sites between 1975 and 1977 (Table 2). For example at Site C, in 1977 no petroleum was recorded within the quadrats although petroleum was observed adjacent to quadrat C-5. In 1975, petroleum was recorded in quadrats C-5 and C-8.

The quadrats surveyed at site E in 1975 and 1977 were separated by a few hundred yards but there still was a high concentration of visible petroleum in the upper intertidal areas at quadrats E-1 and E-2. At quadrat E-2 in 1977, there was fresh looking mousse buried 18 inches (45.72 cm) below the surface of the sand.

Quadrats G-1, G-2, G-3, G-4 were lower in the intertidal area in 1977 than in 1975. These quadrats still had a mousse like substance under the rocks in January 1977 (38% in quadrat G-3). Analyses of the petroleum in quadrats G-3 and G-4 showed that the n-paraffin content was low but that the methyldibenzothiophenes as well as dibenzothiophenes were present. This is interpreted to mean that these samples were protected from dissolution and evaporative weathering but subjected to

microbial degradation. While Metula oil was recorded in the other five quadrats at G in 1975, none was recorded in these quadrats in 1977 (Table 2).

Table 2
Comparison of Metula Oil in Sediments in 1975 and 1977

Site/ Quadrat	Visible Presence a 1975	Visible Presence a 1977	Chemical Analyses: Petroleum Contamination 1975	Petroleum Contamination 1977	$C\ Cl_4$ Extractables % b 1975	$C\ Cl_4$ Extractables % b 1977
A-1	0	0	no	no	< 0.05	< 0.05
A-2	0	0	no	no	< 0.05	< 0.05
C-1	0	0	no	no	< 0.05	< 0.05
C-2	0	0	no	no	< 0.05	< 0.05
C-3	0	0	no	no	< 0.05	< 0.05
C-4	0	0	no	no	< 0.05	< 0.05
C-5	3	0	yes	no	20.8	< 0.05
C-6	0	0	no	no	< 0.05	< 0.05
C-7	0	0	no	no	< 0.05	< 0.05
C-8	3	0	yes	no	3.6	< 0.05
C-9	0	0	no	no	< 0.05	< 0.05
G-5	0	2*	yes	no	< 0.05	< 0.05
G-6	10	0	yes	no	0.061	< 0.05
G-7	10	0	yes	no	0.060	< 0.05
G-8	0	0	yes	no	< 0.05	< 0.05
G-9	0	0	yes	no	< 0.05	< 0.05
H-1	2	0	yes	no	0.082	< 0.05
H-3	10	8	yes	yes	16.2	4.87
H-4	0	6	yes	yes	0.35	< 0.05
I-1	10	3	yes	yes	6.8	0.21
I-2	10	1	yes	yes	11.5	0.023
I-3	10	1	yes	yes	5.7	0.18
I-4	10	10	yes	yes	37.9	8.24
I-5	10	10	yes	yes	9.7	2.17
I-6	10	10	yes	yes	32.5	5.4
X-1	0	1*	no	no	< 0.05	< 0.05
X-2	0	0	no	no	< 0.05	< 0.05
X-3	0	0	no	no	< 0.05	< 0.05
X-4	0	0	no	no	< 0.05	< 0.05

a = number of subsamples where petroleum was visible. b = gravimetric method on surface sediment samples. * = tar was from sources other than Metula.

At site H, much of the area had an asphalt pavement like appearance in 1977. Quadrat H-3 was typical of this with some asphalt pavement from the oil spill and some area eroded away to expose gravel. No visible petroleum was recorded on the surface of quadrats H-1, H-2, H-4 in 1977. However, several small pieces of petroleum were found in the

sediment cores collected in H-4. Quadrat H-4 is in a drainage channel and was surveyed in 1975 because it was never out of water at low tide, and bore no visible petroleum. Most of the surrounding areas were several inches higher, were out of water at low tide, and bore visible petroleum.

Site I remains heavily oiled with mousse about 4 inches thick still on top of the sediment in the marsh quadrats (I-4, I-6) and oil penetrating deeper than the cores into the sediment (20 cms). No quadrat at this site was unoiled in 1977 and mousse still remained on the surface of quadrats I-1 and I-5, the lower intertidal quadrats on the open coast.

The control sites A and X still do not show visible surface evidence of Metula oil contamination such as recorded at the other sites. Several small specks of petroleum (less than 1 gm) were recorded in the screens at X-1. They probably did not originate from the Metula oil spill as indicated earlier. In 1975, 27 quadrats contained oil from the Metula while in 1977 only 11 quadrats contained oil from the Metula.

No petroleum hydrocarbons were detected in the tissues of mussels (*Mytilus edulis chilensis*) collected at sites A and X in 1975 and at sites C and X in 1977 (Table 3). The levels in the tissues from sites G and X were high (1010 to 5580 μg/g wet weight) in 1975. In 1977, low levels of contamination were still present in quadrats at sites E,G,H (5 to 30 μg/g wet weight).

Table 3
Hydrocarbons (μg/g wet weight) in Tissues of *Mytilus edulis chilensis*

Quadrat	1975	1977
A-1	11	
C		2
E		5
G-1	2140	
G-3	3040	10
G-4	5580	
H-2	1320	30
H-3	1010	
X-2	16	2

THE INVERTEBRATES

Table 4 presents a list of intertidal invertebrate species collected in January 1975 and January 1977. This includes some species collected by other than the ten replicate samples taken in each quadrat. A total of 92 species and over 6600 animals were collected by the ten replicate sampling methods on both surveys. It is not surprising to note that some of the species collected in 1977 were not

Table 4. List of Species Collected on Intertidal Surveys in January 1975 and January 1977

PORIFERA**

ANTHOZOA?**

PRIAPULA?**

BRYOZOA**
- Memipea patagonica (water-worn specimen)

NEMATODA

NEMERTEA

SIPUNCULOIDEA

ANNELIDA
- Oligochaeta
  - Unidentified species
- Polychaeta
  - Arabellidae
  - Aricidea (Aedicera) belgicae**
  - Brania sp.*
  - Boccardia polybranchia
  - Capitella capitata
  - Cauleriella? sp.**
  - Ceratocephala sibogae
  - Chaetozone sp.*
  - Cirratulidae
  - Cirratulus cf. cirratus
  - Cirriformia filigera**
  - Dorvileidae**
  - Eteone cf. aurantiaca**
  - Eteone rubella*
  - Euzonus furcifera
  - Exogone sp. (dominant)
  - Exogone sp.*
  - Fabricia sp.**
  - Flabelligera cf. bicolor**
  - Glycinde cf. armata**
  - Harmothoe sp.**
  - Hauchiella sp.*
  - Isocirrus sp.*
  - Lagisca cf. lamellifera*
  - Lumbrineridae**
  - Lumbrineris cf. magalhaensis**

ANNELIDA
- Polychaeta
  - Lumbrineris latreilla
  - Lumbrineris sp.
  - Maldanidae**
  - Namanereis quadraticeps**
  - Nephtyidae**
  - Nereidae**
  - Nereis eugeniae
  - Notocirrus cf. chilensis
  - Notocirrus cf. lorum**
  - Notomastus cf. latericeus
  - Onuphidae
  - Onuphis dorsalis
  - Orbiniidae**
  - Phyllodocidae
  - Platynereis magalhaensis**
  - Polydora cf. socialis**
  - Polynoidae**
  - Pseudomalacoceros sp.**
  - Rhynchospio cf. glutaea
  - Scoloplos (Leodamas) cf. cirratus**
  - Sphaerosyllis sp.**
  - Spionidae**
  - Streblosoma sp.**
  - Syllides sp.**
  - Syllis (Typosyllis) anops
  - Terebellidae
  - Tharyx sp.**
  - Thelepus cf. setosus
  - Travisia olens
  - Typosyllis prolixa**
  - Typosyllis sp.**
  - Typosyllis?

ARTHROPODA
- Crustacea
  - Amphipoda sp.**
  - Balanus sp. (Dead)**
  - Calliopidae**
  - Chthamalus? scabrosus**
  - Corophium sp.**

* = Recorded in 1975 only; ** = Recorded in 1977 only.

Table 4. (Cont'd). List of species Collected on Intertidal Surveys January 1975 and January 1977

ARTHROPODA
Crustacea
Edotea transversa
Eurypodius latreillei
Exosphaeroma gigas
Exosphaeroma studeri**

Harpacticoida**
Halicarcinus planatus
Hyale sp.**
Lysianassidae**
Macrochiridothea michaelseni*
Monoculodes sp.**
Paramoera sp.
cf. Pontogenia sp.**
Serolis*
Tanaidacea juvenile**
Valvifera.*

Pycnogonida
Achelia assimilis**
Tanystylum styligeum**

Insecta
Chironomidae larvae**
Cyclorrhapha larvae**
Cyclorrhapha pupae**
Unidentified larvae*

MOLLUSCA
Gastrapoda
Buccinidae sp. A**
Fissurella cf. picta**
Nacella concinna**
Nacella fuegensis**
Nacella magellanica magellanica
Northia plumbea
Photinula caerulescens**
Photinula cf. expansa**
Rissoidae sp. A**
Siphonaria (Liriola) lessoni**

MOLLUSCA
Gastrapoda
Sphenia hatcheri**
Thiasidae sp.**
Trophon decolor**
Trophon greversianus**

Pelecypoda
Aulacomya sp.**
Lasaea cf. petitiana**
Mytilus edulis chilensis
Pelecypoda sp. A
Pelecypoda sp. B.**
Perumytilus purpuratus**

Polyplacophora
Ischnochiton sp.**
Polyplacophora sp. A**
Polyplacophora sp. B**

ECHINODERMATA
Asteroidea
Unidentified species**

Ophiuroidea
Ophiactis asperula**

* = Recorded in 1975 only; ** = Recorded in 1977 only.

collected in 1975. However it is surprising to record the reverse trend in 9 species. These differences in species composition were not limited to rare species.

Relative species abundance data by quadrat were analyzed for both surveys and arranged in a two-way table (Figure 2). The relative abundance of tar in each quadrat in terms of percent cover is superimposed on the two-way table. The two-way table was formed using classificatory techniques and the Bray-Curtis distance (Straughan 1977).

Site group 1 is characterized by the presence of oligochaetes and virtual absence of other species. Site groups 2 and 3 are characterized by quadrats bearing the mussel M. edulis chilensis. The crustacean Edotea transversa is found in most quadrats in site group 2. However, few other species were recorded in site group 2 while a wide variety of species were recorded in site group 3. Site group 4 is composed of quadrats containing very few species (1 to 3) while no invertebrates were recorded in quadrats in site group 5. Site group 6 contains quadrats from the low intertidal beach at site C and is characterized by a polychaete community.

Most of the heavily oiled quadrats are in site group 5 (Figure 2). Those not found in site group 5 bore only 1 species except for quadrat H-3 which bore 2 species in 1977.

Comparison of number of species, specimens and diversity index (Shannon-Weiner H') from comparable surveys indicates an increase in all three diversity measurements at all sites except sites A and I (Table 5). At site I this is interpreted to be the results of prolonged impact of petroleum while at site A it is speculated to be due to organic enrichment of the area.

Table 5
Comparison of Number of Species, Number of Specimens, and Species Diversity Index (H')

Site	Species 1975	Species 1977	Specimens 1975	Specimens 1977	Diversity Index 1975	Diversity Index 1977
A	9	3	24	11	0.78	0.43
C	19	30	860	784	0.51	0.68
G (5,6,7,8,9)	0	8	0	16	-	0.68
H (1,2,3,4)	19	50	462	4,508	0.81	1.00
H (1,2,3)	8	37	329	1,156	0.33	0.90
I	2	0	7	0	-	-
X	14	24	467	1,363	0.63	0.87

( ) indicates data from these quadrats only, are being compared.

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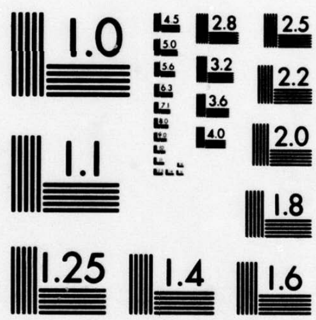
1.0
4.5
5.0
5.6
6.3
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

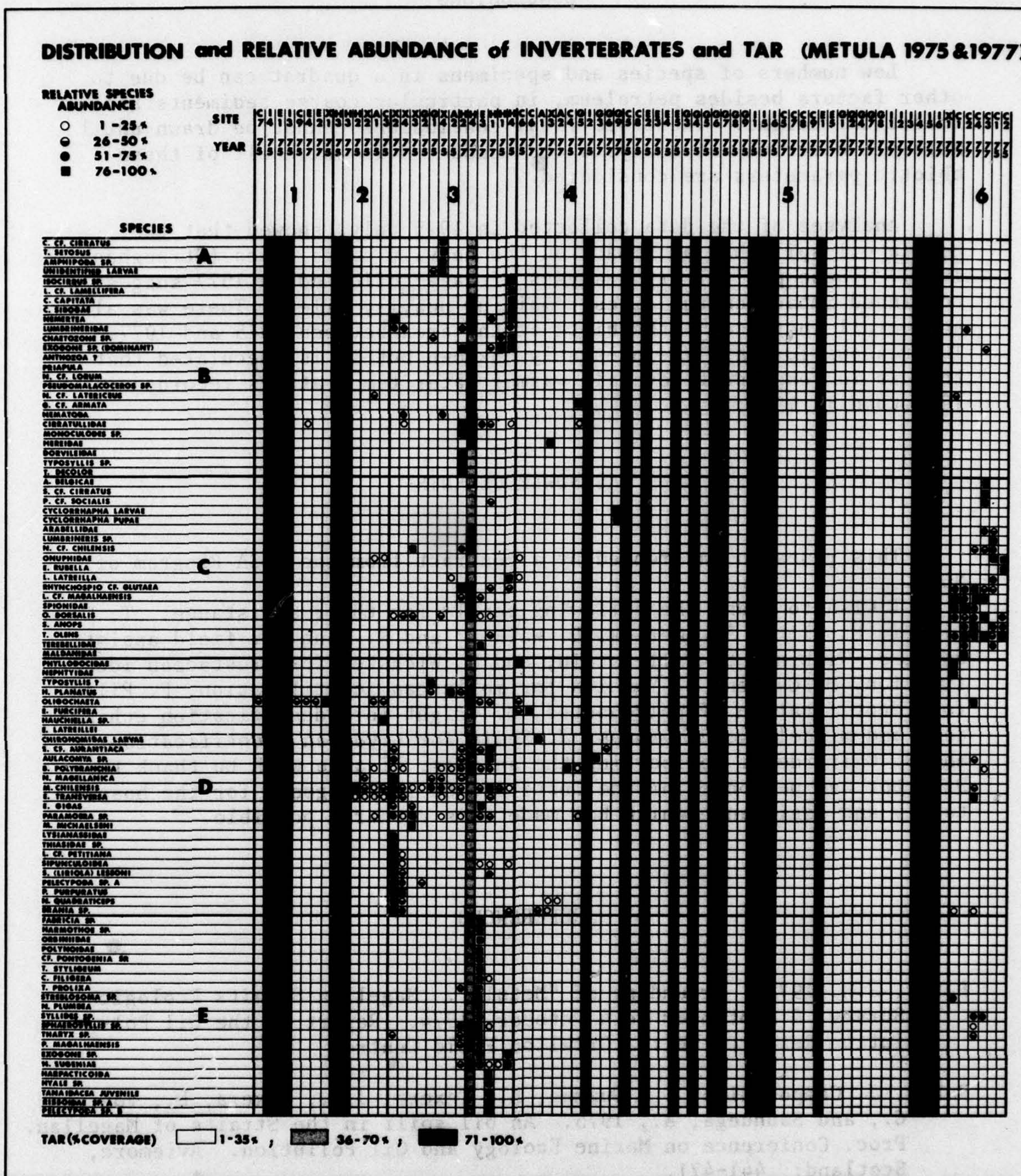

Figure 2. Two-way table relation of the distribution and relative abundance of invertebrates with an overlay to show visible petroleum (referred to as tar) coverage in each quadrat. No shading indicates no visible tar coverage on the quadrat surface.

CONCLUSIONS

Low numbers of species and specimens in a quadrat can be due to other factors besides petroleum, in particular coarse sediments and intertidal height. Therefore final conclusions cannot be drawn until multiple discriminant analyses are conducted in which all of these abiotic parameters are considered.

Analyses of the data collected in 1975 only, showed that the Metula oil spill had an impact on the heavily oiled sites (Straughan 1977). These preliminary analyses of data collected in 1977 suggest a continued impact on the sites remaining heavily oiled. There was also an overall increase in the biota of the area between 1975 and 1977. The reasons for this are presently unknown but it is speculated that this is in response to overall warmer water temperatures recorded in 1977 than in 1975.

ACKNOWLEDGEMENTS

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SINKING OF OIL IN LOS ANGELES HARBOR, CALIFORNIA FOLLOWING THE DESTRUCTION OF THE SANSINENA

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ABSTRACT

Burning of the Bunker C fuel supply from the SANSINENA following a fire and explosion aboard the vessel in Los Angeles Harbor on December 17, 1976 resulted in the sinking of residual material. Computer simulations of the fate of Bunker C exposed to high temperatures indicate that a loss of about 45 percent of the lower molecular weight material will increase the density of the remaining material so that it sinks rapidly in normal sea water. Subsequent modification of the remaining oil at the sediment/water interface by natural processes such as dissolution and biodegradation is extremely slow. The residence time of the sunken oil that remains in Los Angeles Harbor is therefore controlled primarily by the rate of burial by burrowing organisms and sediment accumulation.

INTRODUCTION

Oil spills on water create a variety of problems ranging from concern about damage to organisms to esthetics of shorelines and safety of humans in the event of fire or explosions. When oil is released at the water surface the subsequent sequence of events which determine its fate are to a great extent controlled by environmental conditions during the history of the spill. In addition, the type of oil spilled also regulates the rate at which processes modify oil in the environment. These two sets of factors encompass an extremely large number of parameters which have variable reaction rates and thus lead to a complex series of interactions.

Considerable effort has been expended on evaluating the processes and parameters which combine to determine the fate of oil spills. As an example, several review studies have outlined the status of research on the fate of spilled oil and have summarized areas where additional work is needed

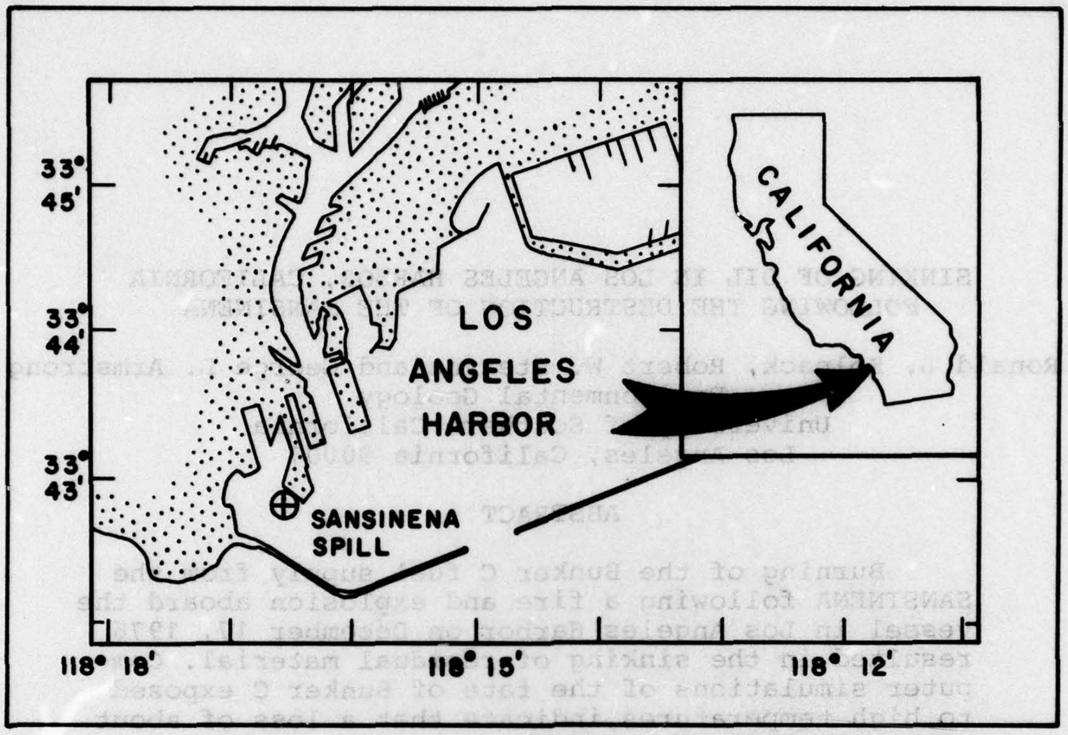

Figure 1. Location of the SANSINENA oil spill.

(Defence Research Information Centre 1973, Kolpack et al 1973, National Academy of Sciences 1975). More recently, Kolpack and Plutchak (1976) described the elements of a three dimensional computer simulation model which was developed to study the fate of oil released on a water surface. This type of approach is an important aspect of efforts to gain a better understanding of the mechanisms that modify oil in the environment; and to develop methods for predicting the behavior of a given oil spill in order to design effective containment and clean-up plans that will alleviate possible damage from the spill.

Up to this time, however, the main emphasis on elucidating the processes which determine the fate of spilled oil has been on the natural conditions that modify oil in the marine environment. One situation that has not received much attention is the influence of burning a portion of the oil as a result of accidental or deliberate means. For instance, a fire and explosion aboard the SANSINENA in Los Angeles Harbor (Figure 1) on December 17, 1976 resulted in the sinking of a significant portion of the ship's fuel supply to the bottom of the harbor. Although the burning of oil in this incident was accidental, some consideration has been given to attempting to burn oil that poses a threat to nearby beaches or other areas, such as fishing grounds, with significant natural resources (Grose and Mattson 1977). This possibility is considered to be an attractive solution by some individuals in

order to reduce the potential threat of, for example, oil tankers wrecked in a particularly vulnerable location.

The limited amount of information on the possible impact from this type of situation suggested that an investigation should be carried out to evaluate the effect of burning on the fate of the residual oil. The following sections outline the results of a computer simulation model study of the major processes that influenced the fate of Bunker C oil from the destruction of the SANSINENA. Some Bunker C from ruptured terminal pipelines was also spilled in the harbor and an evaluation of the fate of that oil is included in this study.

METHODS AND APPROACH

A representative sample of the Bunker C fuel supply aboard the SANSINENA could not be obtained for analysis. Since the composition of the oil involved in a spill incident is an integral component of techniques developed to assess the fate and effects of a spill, we decided to use the composition of a "standard" Bunker C in our computer simulation experiments. Selection of a standard for Bunker C, however, is somewhat difficult owing to the variable amounts of "cutter stock" commonly added prior to loading. This "cutter stock" is essentially a low molecular weight product with a higher rate of evaporation than the basic #6 fuel oil. Hence, most of this material is lost during the initial stages of burning and small errors in the percentage of the "cutter stock" would not significantly affect the longer term fate of the residual material in this particular situation. Therefore, the compositional data for a Bunker C standard that was established by the American Petroleum Institute (Pancirov 1974) were used for the experiments. These data are outlined in Figure 2 and will be referred to again when the results of the simulation experiments are discussed.

A description of the physical and chemical principles involved in the combustion of hydrocarbons is beyond the scope of this study. But, two factors, temperature and the entrainment of air, are of importance in a model simulation study of oil involved in a fire. The conditions which led to the initial ignition of the SANSINENA fuel supply resulted, in part, from an accumulation of volatile hydrocarbons that had evaporated at atmospheric pressure and at a relatively low temperature. The lack of transport of hydrocarbon vapors away from the vessel presumably resulted from a low wind speed in the area during refueling operations. After ignition the conditions changed considerably and the available wind velocity measurements are of limited value. In addition, Gaydon and Wolfhard (1953) summarize information that shows there is a rapid increase in flame temperature within a short distance above the fuel supply. However, even though the temperature of a liquid fuel in an open container does

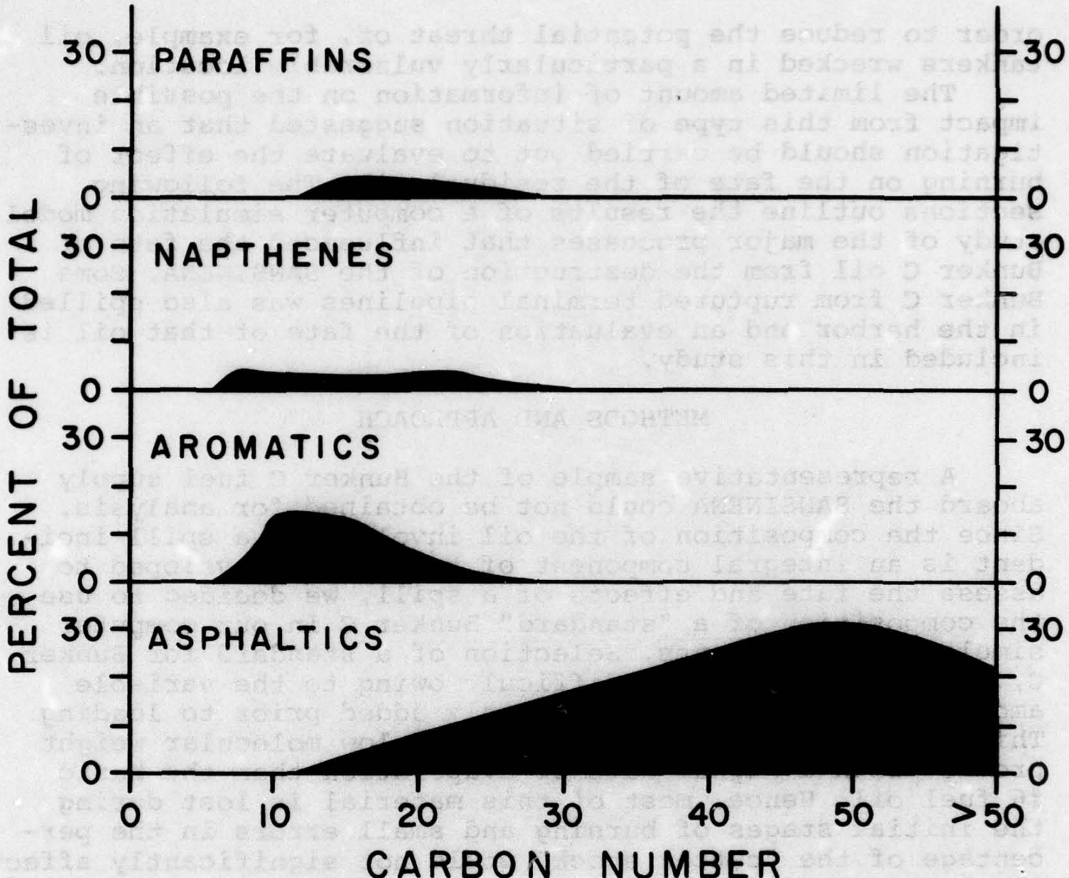

Figure 2. Classification of an American Petroleum Institute standard Bunker C used for computer simulation model study of SANSINENA oil spill.

increase as burning of the vapor proceeds, the temperature of the liquid fuel is considerably lower than the temperatures attained in the actual flame. In our study, simulations at a variety of oil temperatures indicated that the physical properties of Bunker C were modified at an extremely rapid rate when the temperature exceeded approximately 200°C. We therefore elected to confine our evaluations to a temperature range of 25°-250°C.

Entrainment of air during the fire was also of interest because it had a direct effect on the rate of evaporation and on the advection of oil spilled on the water. Estimates of about 300 meters for the upper height of the flames indicate that the fire entrained a considerable amount of air from the area immediately around the vessel. We assumed that this entrainment was from the entire circumferance of the fire but that only the induced wind from the seaward side of the dock area would affect processes such as spreading and mixing. Accordingly, we experimented with a variety of wind speeds from the southwest and found that a minimal

speed of about 13 m/sec in the immediate vicinity of the fire effectively contained any oil on the water within a small area next to the dock. Consequently, simulations of the evaporative losses resulting from the range of temperatures mentioned previously were all run with this wind velocity.

RESULTS AND DISCUSSION

The rate at which the process of evaporation of petroleum hydrocarbons occurs depends primarily on temperature, wind speed, surface area of the petroleum, vapor pressure of the components and the concentration of the components in the petroleum (Adam 1956, Hess 1959, Handbook of Chemistry and Physics 1967, Kreider 1971, Smith and MacIntyre 1971, Sivadier and Mikolaj 1973, Mackay and Matsuga 1973). This process modifies the oil composition primarily on the basis of molecular weight and appears to be practically consistent regardless of the chemical class (Blumer et al 1970). Hence, an increase in temperature will result in a simultaneous loss of a given carbon number range from each chemical class if all other environmental conditions are constant.

A series of computer simulation experiments, based in part on the above conditions, was run for oil temperatures of 25^{o}, 75^{o}, 125^{o} and 250^{o}C in order to determine the resultant changes in Bunker C composition and the ensuing changes in some of the physical properties of the residual material. The initial percentage of each chemical class in the Bunker C used for this study is outlined by the uppermost curves in Figure 3. The amount of material remaining in each class after two hour simulation experiments is also outlined for each of the four temperatures. Owing to the distribution of molecular weight components in this Bunker C, the relative effects of variations in temperature on evaporative losses from all chemical classes are aptly summarized by the changes which occur in carbon number groups 9-12 and 12-18 (Figure 4). These charts illustrate that only a small amount of the original Bunker C with a carbon number of less than 12 remains after a two hour period when the oil temperature is 75^{o}C. On the other hand, an oil temperature of 250^{o}C will not result in a significant loss of material in the greater than carbon number 27 group.

Evaporative losses therefore significantly alter the composition of oil and can lead to other modifications which are important factors in determining the fate and effect of an oil spill. An example of a direct consequence of modifications brought about by losses due to evaporation is illustrated by changes in oil density with respect to time and temperature (Figure 5). Since the process of evaporation removes the lighter molecular weight material, there is a concomitant increase in oil density. Although evaporation affects other processes such as spreading, dissolution and microbial degradation, a major change in environmental control will occur if the density of oil exceeds that of the

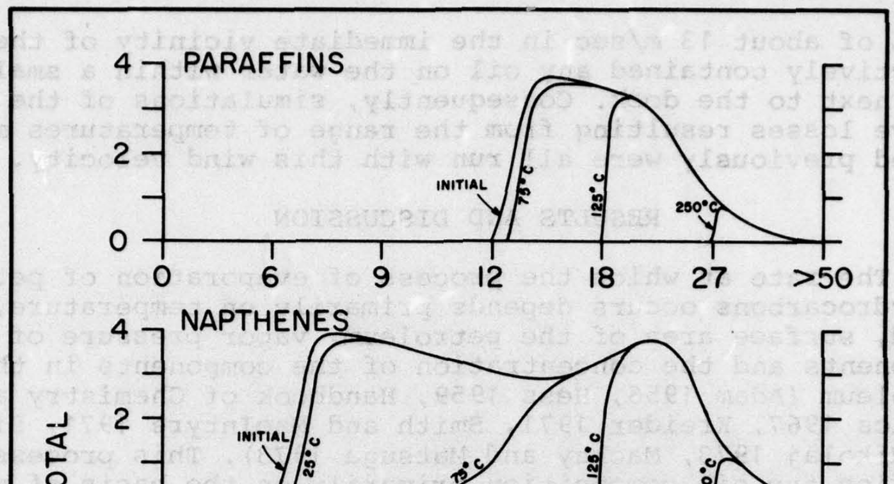

Figure 3. Changes in composition of a Bunker C after two hours of evaporation at four different temperatures. Note change of scale for percent of each chemical class.

underlying water. Oil with a specific gravity of more than 1.025 will commence to sink in normal sea water when the buoyant forces are not sufficient to keep it at the water surface. Characteristically, turbulence created by wind and wave activity tends to promote mixing of oil into the water column. When mixing of oil with a density greater than that of sea water occurs, the particles of oil will tend to continue settling to the sediment/water interface. In the simulation experiments run for this study, the Bunker

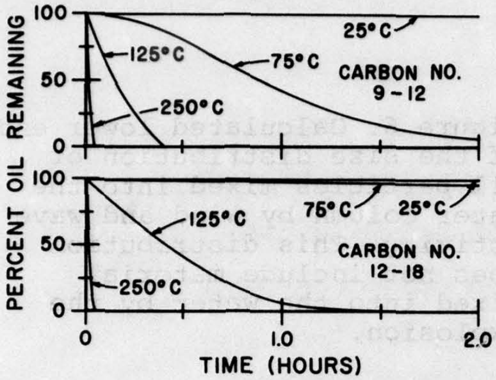

Figure 4. Evaporative losses in carbon number groups 9-12 (top) and 12-18 (bottom) after two hours at four different temperatures.

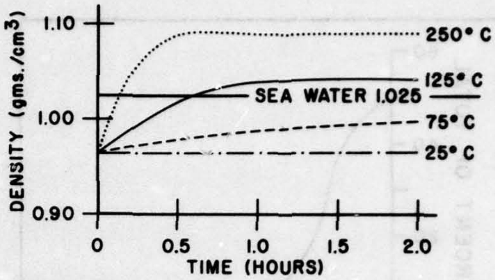

Figure 5. Changes in density of a Bunker C with respect to time at four different temperatures.

C oil increased to the density of sea water within a period of about ten hours when the oil temperature was 75°C. At higher temperatures the oil density increased very rapidly. For example, a specific gravity of 1.025 was attained after about 40 minutes at a temperature of 125°C and within less than 10 minutes at a temperature of 250°C.

The high rate of increasing density during the initial stages of burning thus enhances the possibility of having the residual, or heavier, components of the oil sink below the water surface. In the area surrounding the SANSINENA spill the water depth is an average of 15 meters. Consequently the time of transit to the bottom is relatively short. Subsurface currents in the water column of Los Angeles Harbor are dominated by the influence of tidal movements. These currents prolong the transit time somewhat but the main effect is deposition of oil over a larger area than if there were no subsurface water currents.

As mentioned previously, water turbulence promotes mixing and increases the potential of oil particles to settle through the water column. Energy introduced to the system by wind and wave activity also results in a mixing of low density oil particles downward into the water column. Field measurements of the size and concentration of oil that can be introduced to the water column by mixing are rather sparse owing to sampling and analytical difficulties. Information from investigations of the ARROW spill by Kranck and Sheldon (1970), Forrester (1971) and Levy and Walton (1972), as well as a study by Masch (1963) on waste material, served as a basis for calculating oil particle sizes in the Los Angeles Harbor water column immediately after the SANSINENA incident occurred. These calculations yielded an estimate for the lower end of the particle size distribution (Figure 6), but other evidence suggests that a considerable volume of oil in particles larger than 1.0 mm reached the sediment interface. Some of this evidence is related to the fact that there was

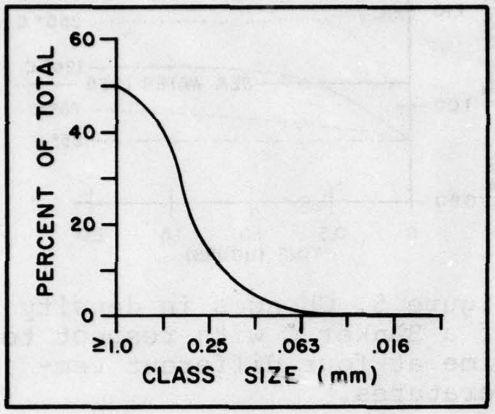

Figure 6. Calculated lower end of the size distribution of oil particles mixed into the water column by wind and wave activity. This distribution does not include material mixed into the water by the explosion.

also a considerable amount of turbulence in the immediate vicinity of the spill as a result of the fire, but especially when an explosion lifted a portion of the mid-section of the SANSINENA out of the water and deposited the debris on the adjacent dock area. The turbulence in the shallow water system created by the explosion was sufficient to drive large and small particles down to the bottom. Globules of oil that came into contact with fine-grained (silt and clay) sediments would then invoke a secondary process of adherance which would tend to keep the majority of oil on the bottom (Kolpack 1971, Meyers and Oas 1978).

Even oil particles with densities less than that of sea water presumably would remain at the bottom under natural conditions in Los Angeles Harbor because the subsequent degradative processes would tend to increase the density of this oil by removing or modifing the lighter molecular weight components first. However, large deep-draft vessels frequently maneuver in the area where oil sunk to the bottom. Turbulence created by these vessels could be sufficient to disaggregate some of the oil deposits and the resuspension of low density oil would permit this material to ascend to the water surface.

One objective of this study was to estimate the length of time that oil which sank following the SANSINENA incident would be exposed to the environment. Calculating the average composition for oil that sank was rather difficult because several assumptions had to be made. If one assumed that all of the vessels fuel supply was subjected to burning then the problem was somewhat simplier. But, the situation is complicated by the events surrounding the explosion that occurred. It seems more likely that portions of the fuel supply were exposed to high temperatures for only a brief period of time. Therefore, we decided to simulate a situation wherein all components of the Bunker C with a molecular weight of less than 20 carbon numbers were removed by the fire. The calculated composition of the oil which was assumed to reach the bottom sediments is outlined in Figure 7.

Attempts to simulate the changes which a Bunker C oil

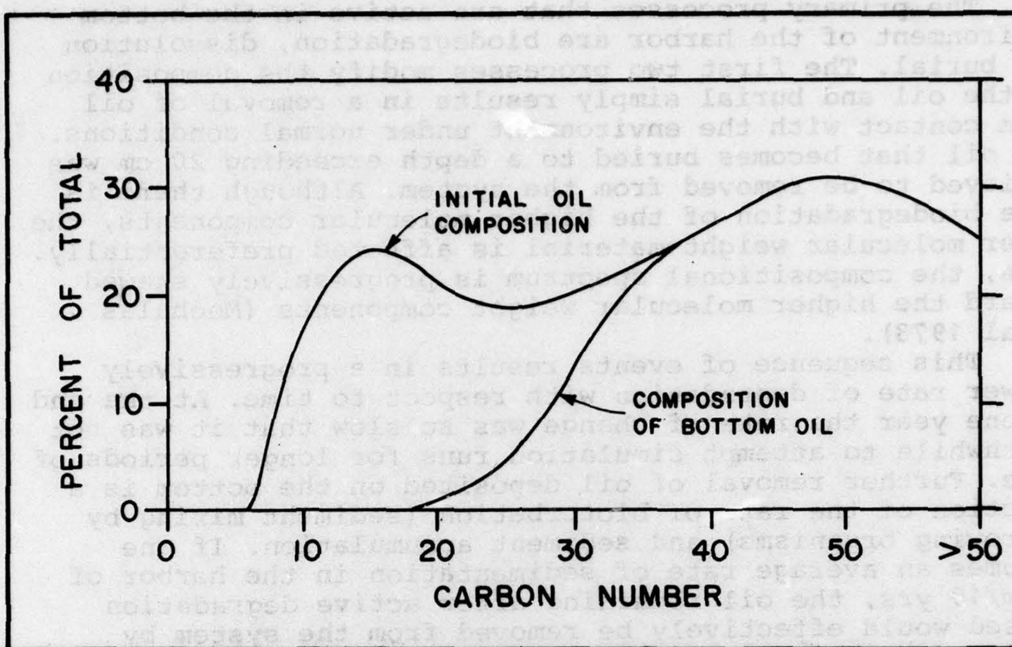

Figure 7. Calculated composition of Bunker C used to evaluate rate of degradation at sediment/water interface. Material between the curves representing composition of original oil and oil at the bottom was lost during burning.

undergoes during a fire and explosion rely basically on assumptions about the rate of burning, amount of material consumed by the fire and the length of time the remaining oil was exposed to elevated temperatures; which would greatly accelerate the loss of oil by evaporation. A long exposure time to elevated temperatures produces a rapid loss of the lower molecular weight material, but the ensuing rate of degradation when the residual oil sinks to the bottom is extremely slow. On the other hand, short to moderate exposure times at lower temperatures do not result in very rapid initial changes, but the rate of subsequent degradation affects a comparatively larger portion of the residual oil.

We have taken a somewhat conservative approach by assuming the original oil was modified by evaporation just long enough for the density to approach that of sea water so that vertical turbulence would promote sinking. This approach yielded a loss from evaporation of about 50% of the original oil. Passage through the water column resulted in a loss of less than 0.01%, which, as mentioned previously, is an insignificant amount. An additional loss of 1.5% occurred at the sediment/water interface during the first 5 months, primarily as a result of biodegradation. Between 5 months and 10 months after the oil was deposited on the bottom, the additional calculated loss amounted to 5.0% of the oil originally deposited on the bottom.

The primary processes that are active in the bottom environment of the harbor are biodegradation, dissolution and burial. The first two processes modify the composition of the oil and burial simply results in a removal of oil from contact with the environment under normal conditions. Any oil that becomes buried to a depth exceeding 20 cm was believed to be removed from the system. Although there is some biodegradation of the higher molecular components, the lower molecular weight material is affected preferentially. Thus, the compositional spectrum is progressively skewed toward the higher molecular weight components (Mechalas et al 1973).

This sequence of events results in a progressively slower rate of degradation with respect to time. At the end of one year the rate of change was so slow that it was not worthwhile to attempt simulation runs for longer periods of time. Further removal of oil deposited on the bottom is a function of the rate of bioturbation (sediment mixing by burrowing organisms) and sediment accumulation. If one assumes an average rate of sedimentation in the harbor of 1 cm/10 yrs, the oil remaining after active degradation ceased would effectively be removed from the system by burial in approximately 200 years. This residence time is modified by the effect of bioturbation and a more realistic time for complete removal under these conditions is about 100-125 years.

The principal remaining concern was an evaluation of the fate of the Bunker C oil spilled in the harbor from the ruptured pipelines at the dock facility. A seven day simulation experiment was carried out with essentially the same parameters as the previous simulations except the initial oil temperature was set at 20°C and the wind values used were those recorded for the seven day period following the SANSINENA spill.

Evaporation was the dominant process modifing the oil at the water surface following release of this oil (Figure 8). Thereafter, however, the rate of loss from evaporation became slower until it was practically negligible by the fourth day. Dissolution followed a similar pattern, although at a much slower rate than the process of evaporation. On the other hand, there was a relatively constant amount of material mixed into the water column during the second to fourth days following the spill. By the end of the fifth day the amount of material mixed into the water column was also reduced to a relatively minor amount. Biodegradation was not an important process during the first two days, until a microbial population acclimated to degrading oil became established. Subsequently the rate of biodegradation accelerated until the components most susceptible to attack by this process were degraded by the seventh day.

Presumably additional material would undergo biodegradation after a seven day period; but it did not seem worthwhile to extend the simulation period because most of

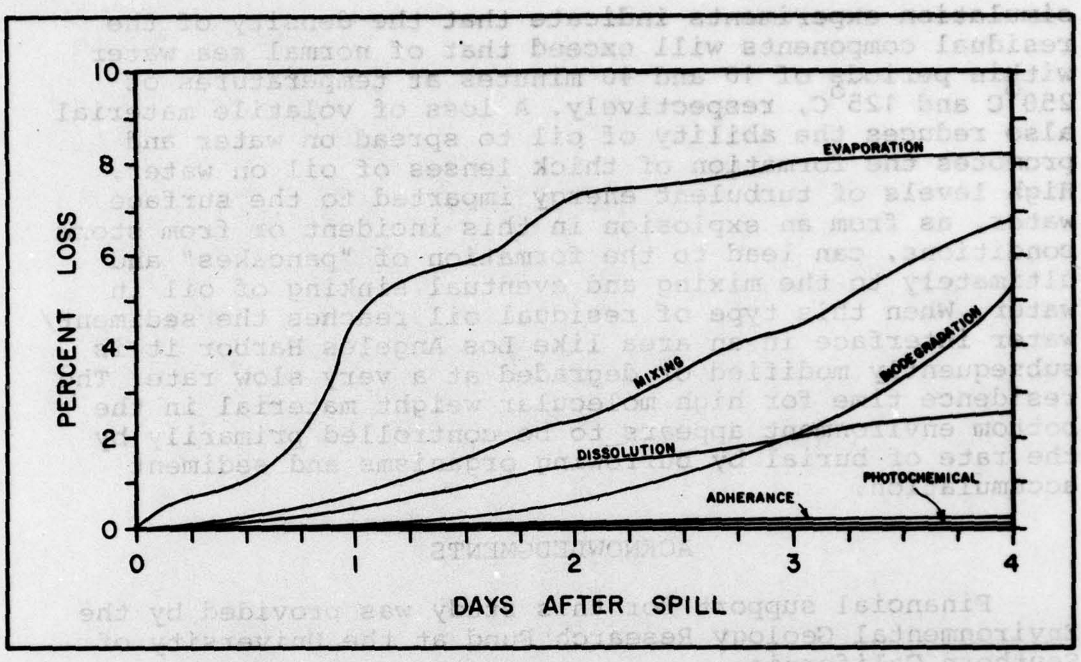

Figure 8. Losses from a Bunker C oil at the surface of Los Angeles Harbor under ambient environmental conditions. The simulation experiment had a starting time of 19:40 hours on December 17, 1976.

the remaining Bunker C had either been removed by clean-up operations or it had contacted the nearby perimeter of the harbor. If the oil spilled from the ruptured pipelines was left to degrade naturally, about 23% of the total volume spilled would disappear from the water surface within four days. At the end of seven days most of the processes ceased to be effective in rapidly degrading the remaining oil. Our calculations also show that the average density of the oil remaining on the water surface after seven days was about 1.022 gms/cm^3. Furthermore, less than 0.1% of the total volume spilled had reached the bottom by this time. Thus, it is evident that the high initial rate of loss of lower molecular weight components during a fire increases the density to the point where it will sink a major portion of the oil within a very short period of time. However, if this Bunker C is left to degrade naturally under the relatively quiescient conditions in Los Angeles Harbor, it takes more than one week for the residual material on the water surface to reach a density approaching that of sea water.

CONCLUSIONS

A rapid loss of lower molecular weight components occurs during the burning of a Bunker C oil and this increases the density of the residual material. Computer

simulation experiments indicate that the density of the residual components will exceed that of normal sea water within periods of 10 and 40 minutes at temperatures of 250°C and 125°C, respectively. A loss of volatile material also reduces the ability of oil to spread on water and promotes the formation of thick lenses of oil on water. High levels of turbulent energy imparted to the surface water, as from an explosion in this incident or from storm conditions, can lead to the formation of "pancakes" and ultimately to the mixing and eventual sinking of oil in water. When this type of residual oil reaches the sediment/water interface in an area like Los Angeles Harbor it is subsequently modified or degraded at a very slow rate. The residence time for high molecular weight material in the bottom environment appears to be controlled primarily by the rate of burial by burrowing organisms and sediment accumulation.

ACKNOWLEDGMENTS

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THE IMPACT OF THE SANSINENA EXPLOSION AND BUNKER C SPILL ON THE MARINE ENVIRONMENT

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ABSTRACT

On December 17, 1976 the 70,000 ton tanker *Sansinena* exploded and burned in Los Angeles Harbor while refueling. The explosion and fire resulted in an estimated spill of 20,000 to 32,000 barrels of Bunker C fuel. Harbors Environmental Projects initiated studies on December 20 on the spread of the oil and its impact on biology and water quality at 24 stations. Studies by HEP at the site provided a baseline from 1972 to December 1976. Intertidal areas evidenced the greatest impact. Benthic population decreased greatly through April but returned to normal by November 1, 1977. Benthic organisms correlated best with oil and grease concentrations in bottom waters rather than in surface sediments, until November when hydrocarbons rose but no longer were correlated (toxic).

INTRODUCTION

The Sansinena Incident

The *Sansinena*, an 850 foot, 70,000 ton tanker of Liberian registry under charter to the Union Oil Company, exploded and burned at the dock at Berth 46 in outer Los Angeles Harbor at 19:40 hours on December 17, 1976 (Figure 1). The ship had apparently completed unloading 500,000 barrels of Indonesian light crude oil and had taken on 22,000 barrels of Bunker C fuel while ballasting under low clouds and foggy conditions, when an unknown incident caused the entire midship section to explode. The superstructure was hurled high into the air and crashed on the dock, behind the chicksans, rupturing valves and lines. An unknown quantity of crude and Bunker C flowed into the harbor beneath the dock and wreckage for several days. This caused intermittent backfiring on the dock, blazing up

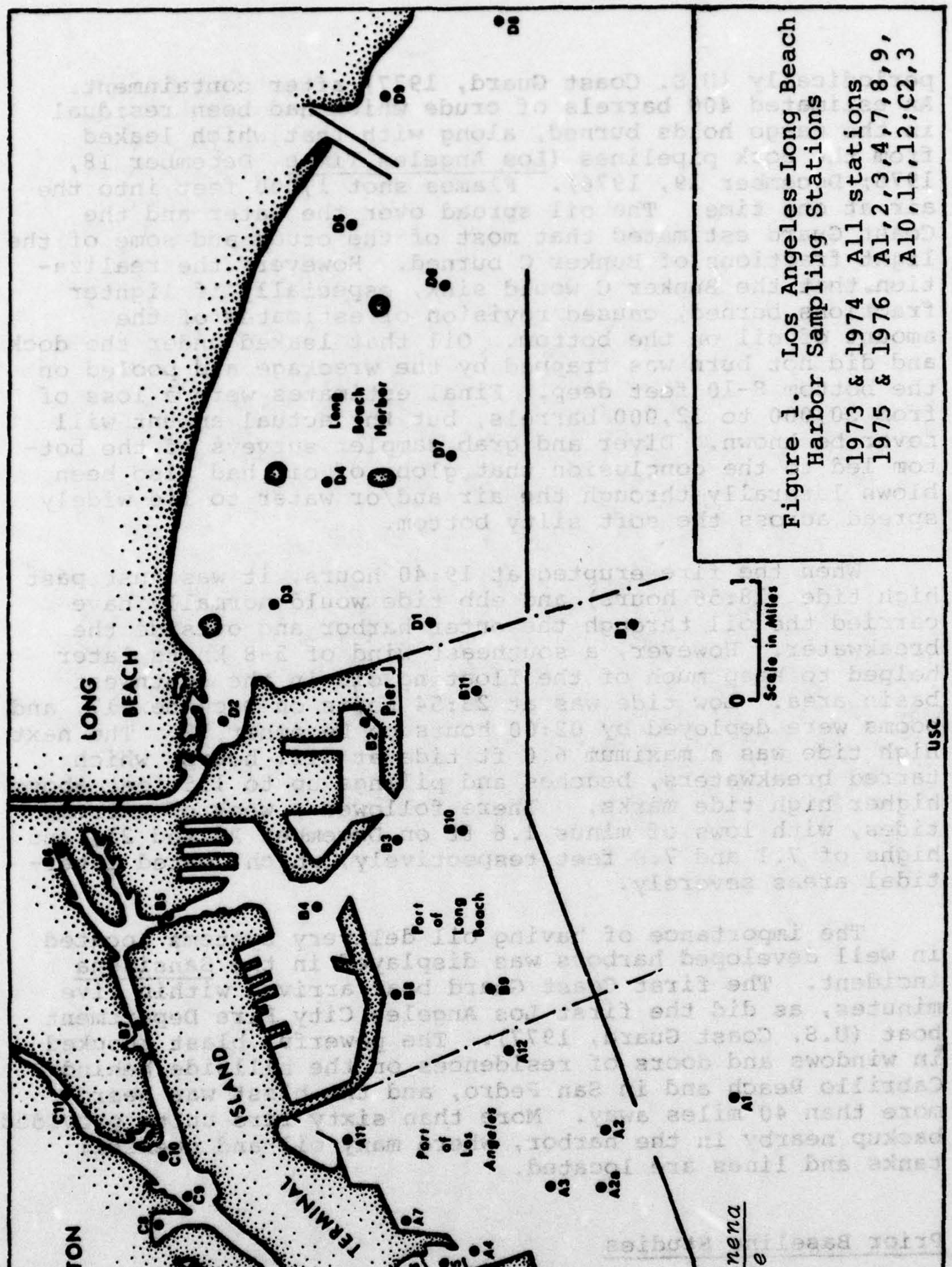


Figure 1. Los Angeles-Long Beach Harbor Sampling Stations
1973 & 1974 All stations
1975 & 1976 A1,2,3,4,7,8,9, A10,11,12;C2,3

periodically (U.S. Coast Guard, 1977) after containment. An estimated 400 barrels of crude which had been residual in the cargo holds burned, along with that which leaked from the dock pipelines (Los Angeles Times, December 18, 1976; December 19, 1976). Flames shot 1,000 feet into the air at one time. The oil spread over the water and the Coast Guard estimated that most of the crude and some of the light fractions of Bunker C burned. However, the realization that the Bunker C would sink, especially if lighter fractions burned, caused revision of estimates of the amount of oil on the bottom. Oil that leaked under the dock and did not burn was trapped by the wreckage and pooled on the bottom 8-10 feet deep. Final estimates were a loss of from 20,000 to 32,000 barrels, but the actual amount will never be known. Diver and grab sampler surveys of the bottom led to the conclusion that globs of oil had also been blown laterally through the air and/or water to lie widely spread across the soft silty bottom.

When the fire erupted at 19:40 hours, it was just past high tide (18:56 hours) and ebb tide would normally have carried the oil through the outer harbor and outside the breakwater. However, a southeast wind of 5-8 knots later helped to keep much of the floating oil in the southwest basin area. Low tide was at 23:54 hours on December 17, and booms were deployed by 02:00 hours on December 18. The next high tide was a maximum 6.6 ft tide at 6:21 hours, which tarred breakwaters, beaches and pilings up to 1.5 feet above higher high tide marks. There followed a week of extreme tides, with lows of minus 1.6 ft on December 20 and 21, and highs of 7.1 and 7.0 feet respectively, which coated intertidal areas severely.

The importance of having oil delivery systems located in well developed harbors was displayed in the Sansinena incident. The first Coast Guard boat arrived within five minutes, as did the first Los Angeles City Fire Department boat (U.S. Coast Guard, 1977). The powerful blast knocked in windows and doors of residences on the hillside behind Cabrillo Beach and in San Pedro, and the blast was heard more than 40 miles away. More than sixty fire units provided backup nearby in the harbor, where many oil and chemical tanks and lines are located.

Prior Baseline Studies

Harbors Environmental Projects at the University of Southern California had carried out monitoring studies at a station (A9=U09) for six years prior to the Sansinena incident. The most recent samples had been taken on December 1, 1976, sixteen days prior to the explosion.

Past biological studies in the area have included monthly primary productivity, chlorophyll *a* and assimilation ratios, microbials, zooplankton species and numbers, meroplankton/fouling fauna and sea birds. Benthic organisms were sampled quarterly; fish trawls were done occasionally. Monthly measurements also included physical parameters such as temperature, salinity, oxygen, pH and turbidity throughout the depth of the water column; nutrients were sampled at the surface. Sediment chemistry and grain size were done occasionally. Table 1 summarizes the methods and references to techniques used.

Multivariate analysis had been carried out on data from 1973 and 1974 (Allan Hancock Foundation, 1976) for the U.S. Army Corps of Engineers. Cooperative funding for the studies included the Corps of Engineers, the Pacific Lighting Corporation (Southern California Gas Company), the Port of Los Angeles and Port of Long Beach, the USC Sea Grant Program (NOAA, Department of Commerce), the Tuna Research Foundation, and others.

This data base appeared to offer the first opportunity to study the impact of Bunker C on the marine environment where prior conditions were known and the impact was confined to a reasonably well defined area. Although it would have been preferable to duplicate all procedures at the proposed impact stations, sufficient funds were not available. The study of the impact of the Sansinena on the marine environment was funded by the Union Oil Company, with assistance from the USC Sea Grant Program and Harbors Environmental Projects, of the Institute for Marine and Coastal Studies.

ANALYTICAL METHODS

Analysis of Data

Hierarchical classification was used to study patterns in the biological data. Groups of biologically similar sampling sites were defined, and these groups were then compared with the patterns in the measured environmental parameters. From this, hypotheses concerning the relationships between the biota and the environment were suggested. Of particular interest, of course, was whether parameters that were possibly related to the ship incident were actually correlated with the pattern of sample-site groupings.

Specifically, flexible sorting (B=-.25) strategy (Lance and Williams, 1967) and the Bray-Curtis distance index (Bray and Curtis, 1957; Clifford and Stephenson, 1975) were used to classify the sampling sites. The benthic species

Table 1. PARAMETERS MEASURED, LOS ANGELES-LONG BEACH HARBORS

A. MONTHLY MONITORING	METHOD
1. Abiotic Parameters	
a. Temperature b. Salinity c. Dissolved Oxygen d. pH	Martek electronic remote probe, at 1m intervals through the water column
e. Light transmittance	Hydroproducts Transmissometer, remote probe with self-contained light path, at 1m intervals through depth
f. Ammonia	Solorzano (1969)
g. Nitrite	Strickland and Parsons (1968)
h. Nitrate i. Phosphate	Modified Strickland and Parsons (AHF, 1976)
2. Biotic Parameters	
a. Biological Oxygen Demand (BOD)	Standard Methods (American Public Health, 1971) modified by Juge and Greist (1975), surface samples
b. Total Coliforms c. Fecal Coliforms d. Fecal Streptococcus	Millepore (1972), AHF (1976)
e. Bacterial Standard Plate Count	Amer. Soc. Microbiol. (1957); AHF (1976)
f. Primary Productivity, Phytoplankton	Modified Steeman-Neilsen (1952) ^{14}C light and dark bottles, standard light source incubator with ambient water temperature
g. Chlorophyll	Spectrophotometry, Strickland and Parsons (1968) equations
h. Assimilation ratio	
i. Zooplankton species	253u net surface tow with flow meter
j. Water column fouling fauna, larvae and juveniles	Glass microscope slides in wood frame rack, plastic screened, suspended at 3m depth

B. QUARTERLY MONITORING	METHOD
1. Abiotic Parameters	
a. Sediment grain size	Pettijohn (1957), Felix (1969), Gibbs (1971), AHF (1976)
b. Trace metals pesticides	Amer. Publ. Health (1971); AHF (1976)
2. Biotic Parameters	
a. Benthic Fauna	Campbell grab or Reinecke box corer, 0.5mm screen
b. Fish species	Otter trawl, gill netting
C. BIWEEKLY MONITORING (OUTER LOS ANGELES HARBOR ONLY)	
1. Abiotic Parameters	
a. Temperature b. Salinity c. Dissolved Oxygen d. pH	Martek electronic remote probe, at 1m intervals through the water column
e. Oil and Grease	Amer. Publ. Health (1971)
2. Biotic Parameters	
a. BOD	Standard Methods (Amer. Publ. Health, 1971) modified by Juge and Greist (1975), surface samples
D. WEEKLY (OUTER LOS ANGELES-LONG BEACH HARBORS) 1973-1974	
1. Biotic Parameters	
a. Bird census	Observations of nesting, resting, feeding and transit

counts in each sample were first transformed by a square root and standardized by a weighted species mean (Smith, 1976). The plankton species counts were transformed by a square root and standardized by a species maximum.

To elucidate the relationships between the species and the sampling site groups defined in the classification, two-way coincidence tables were constructed (Kikkama, 1968; Clifford and Stephenson, 1975). The numbers in the body of the table were 1) transformed and standardized as in the site classification analysis, and 2) converted to symbols, which are as follows:

* > .75 TO 1

+ > .5 TO .75

- > .25 TO .50

· > 0 TO .25

blank 0

To study the relationships between the classification results and the measured environmental variables, bar graphs were constructed for each group on each variable. This showed the levels and variability of each environmental variable in the site groups. This technique has the weakness that it will not show the more complex multivariate (biotic-environmental) relationships. To test for the presence of such relationships, the groups were analyzed for correspondence with the environmental data using multiple discriminant analysis (Smith, 1976). These results did not show any patterns which were not evident in the bar graphs. For this reason the discriminant analysis results are not shown. Shannon-Weiner diversity indices were also calculated.

OIL AND GREASE DISTRIBUTION

In Sediments and the Water Column

December, 1976. Surface sediment samples were taken in locations requested by the Union Oil Company in December, 1976 on the 22nd, 23rd, 24th, 27th, 28th, 29th and 30th of the month. Sampling was limited, and was hampered by the placement of booms and clean-up efforts. A small snapper grab on a hand line was used from a Boston Whaler.

The measurements on December 22 and 23 showed little difference from expected normal levels in the sediment except

where the oil pool near the stern yielded 665,000 ppm. A high reading of 7460 ppm beyond the bow section on December 24 indicated an unexpected spread in that direction, and on December 27 increases in the fairway channel to the east were found up to 6360 ppm.

A rapid increase in oil and grease levels was shown a few days later (Figure 2) in the area sampled, where values from 5,000 to above 7,000 ppm were found, particularly in depressions on the irregular bottom over a wider area. Readings in the area closer to the booms or "sea curtain" were actually lower than those in areas somewhat farther away. Oil and grease at the water surface ranged from 4.20 ppm at the innermost slip down to 0.10 near the main channel at the end of December (Figure 3).

Previous published records for the area are limited; no analyses were done in the areas very close to Cabrillo Beach, so it is not possible to state that higher values did not occur in sediments deposited there prior to the blast. That is unlikely, however, since the highest values found in the harbor in 1973-1974 during a survey by Harbors Environmental Projects were in the 4000 ppm range found in the inner harbor blind end slips and near an oil island in Long Beach. Values in the outer harbor vicinity of Berth 46 ranged from about 1800 to 2100 at that time. More intensive sampling in inner Cerritos Channel (Long Beach) in March 1976 showed a few depositional areas with high readings at the end of slips. This might be expected in areas of low flushing that have not been dredged for some years.

Of interest are the oil and grease levels recorded by Chen and Lu (1974) in the Channel and around Santa Catalina Island. Many of these were higher than harbor levels, even at box core depths of 30 cm; these increased with water depth, suggesting a downward movement along with the finer sediments.

January, 1977. By mid-January, 1977, oil and grease levels had decreased in the sediments at most stations. Figures 3 and 4 offer a comparison, bearing in mind that sampling within the oil pool itself was not carried out.

In the water column, however, some readings had increased, with a high of 6.26 ppm at station UO3 (Figure 5). Bottom water concentrations were also higher in a number of locations.

April, 1977. The stormy weather of the spring months and salvage of the bow and stern sections of the tanker apparently combined to distribute oil anew throughout the

area. The bow was towed to the scrap yard on February 18, 1977 and the stern was towed away April 22, 1977. Hull debris was subsequently cleaned up at the site. Sediment oil and grease levels continued to increase at station UO1, a dead end slip, and values were considerably higher at most sampling locations (Figure 6) than they had been in January. Rain fell throughout the first week of January and near the end of March; temperatures were in the 80-90°F range during mid-January, for several days in February, and in March and April. This may also have affected the oil distribution patterns.

Although concentrations increased in the sediments, the water column concentrations decreased greatly (Figure 7). This might represent a decline in leaching of residual oil into the water column, or it might reflect the tidal phase at the time of sampling. There were tidal highs of +5.4 ft on the 17th and 18th, the latter at the time of sampling. Efforts to vacuum up the pool of oil at the site continued throughout the summer of 1977.

<u>July, 1977</u>. Boxcore samples taken July 18, 1977 were sampled at the top, middle and bottom of the sediment cores to obtain information on the depth of penetration of oil and grease into the sediment. Surface sediment levels had dropped from the April readings at most of the stations sampled. Penetration varied considerably, ranging from being almost uniform at station UO1 to dropping by more than 50 percent from top to bottom of the cores at UO19 and UO21 (Figure 8). This might be related to grain size of sediment, which tends to be finest in the innermost slip areas (AHF, 1976) and is easily transported.

Concentrations in the water column (Figure 9) increased, however, and this could not readily be explained by tides. Inner harbor surface temperatures had risen about 1.5°C, but temperatures at other stations were generally similar for April and July. Increased recreational boating could be responsible, and an upswing in bunkering operations in the outer harbor could also have increased the incidence of slicks. Certainly all of the oil cannot be attributed to the <u>Sansinena</u>. Analysis of some of the "chocolate mousse" on the beach indicated that it was probably not <u>Sansinena</u> oil.

<u>November, 1977</u>. Harbors Environmental Projects sampled the stations again on November 1, 1977 after the conclusion of the Union Oil Company study. Oil and grease measurements were made at the top, middle and bottom of the box core samples (Figure 10). Increases in oil and grease levels occurred at all of the stations over the July readings,

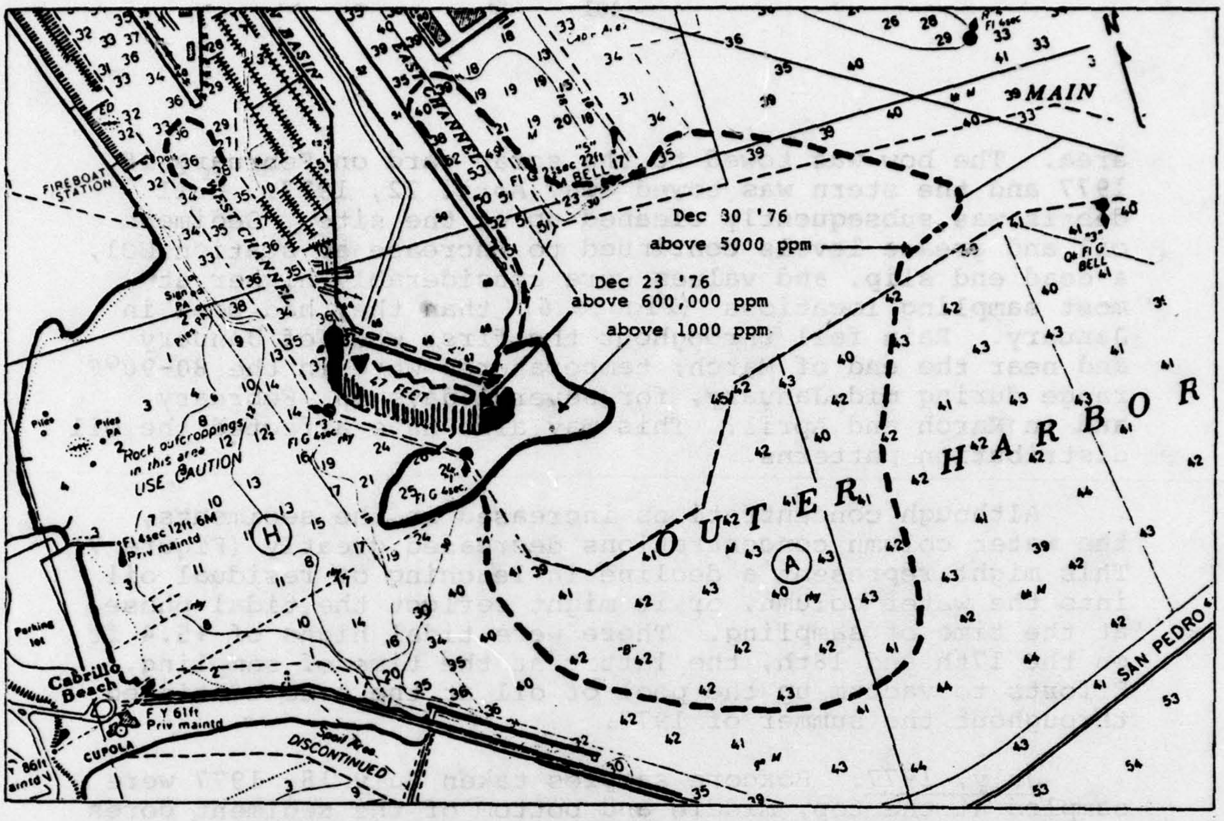


Figure 2. Spread of Oil and Grease in Sediment (sample area restricted by booms).

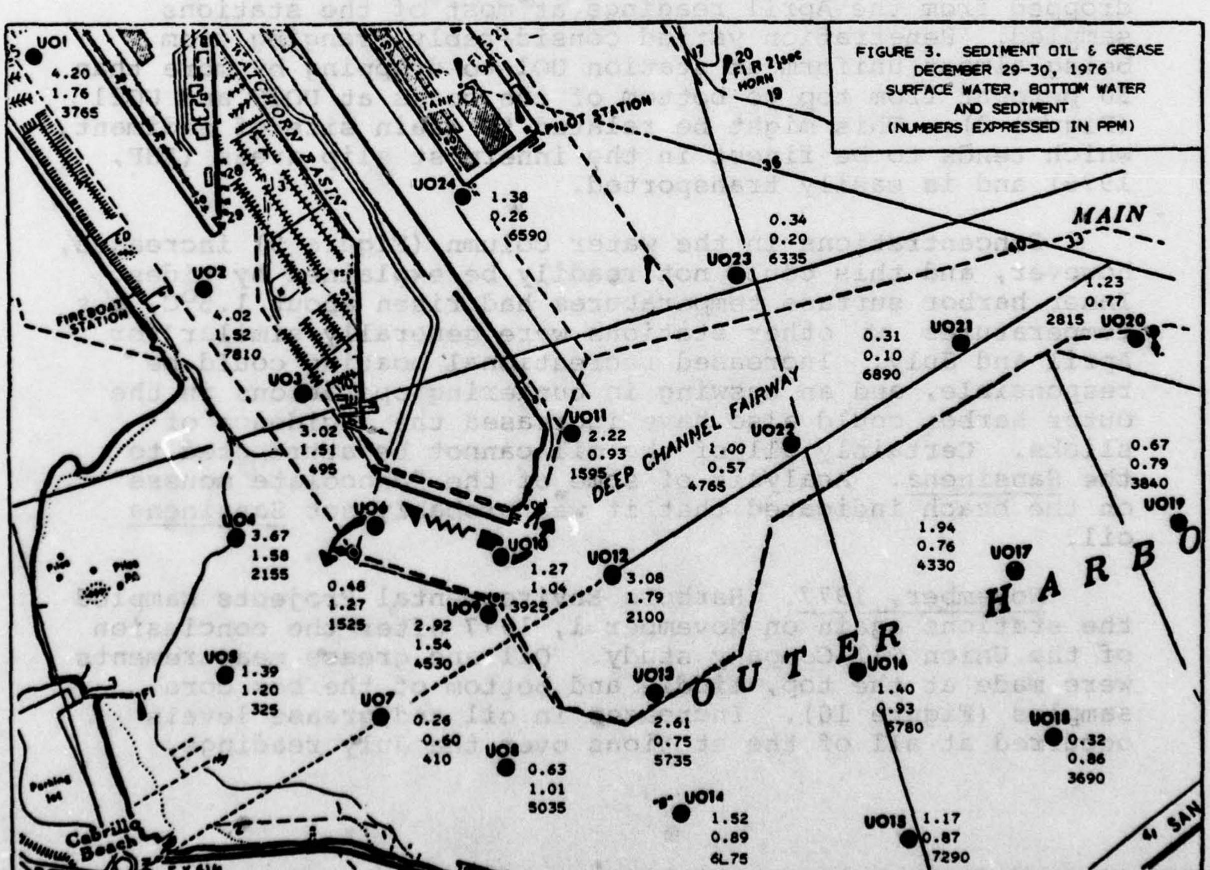


FIGURE 3. SEDIMENT OIL & GREASE DECEMBER 29-30, 1976 SURFACE WATER, BOTTOM WATER AND SEDIMENT (NUMBERS EXPRESSED IN PPM)

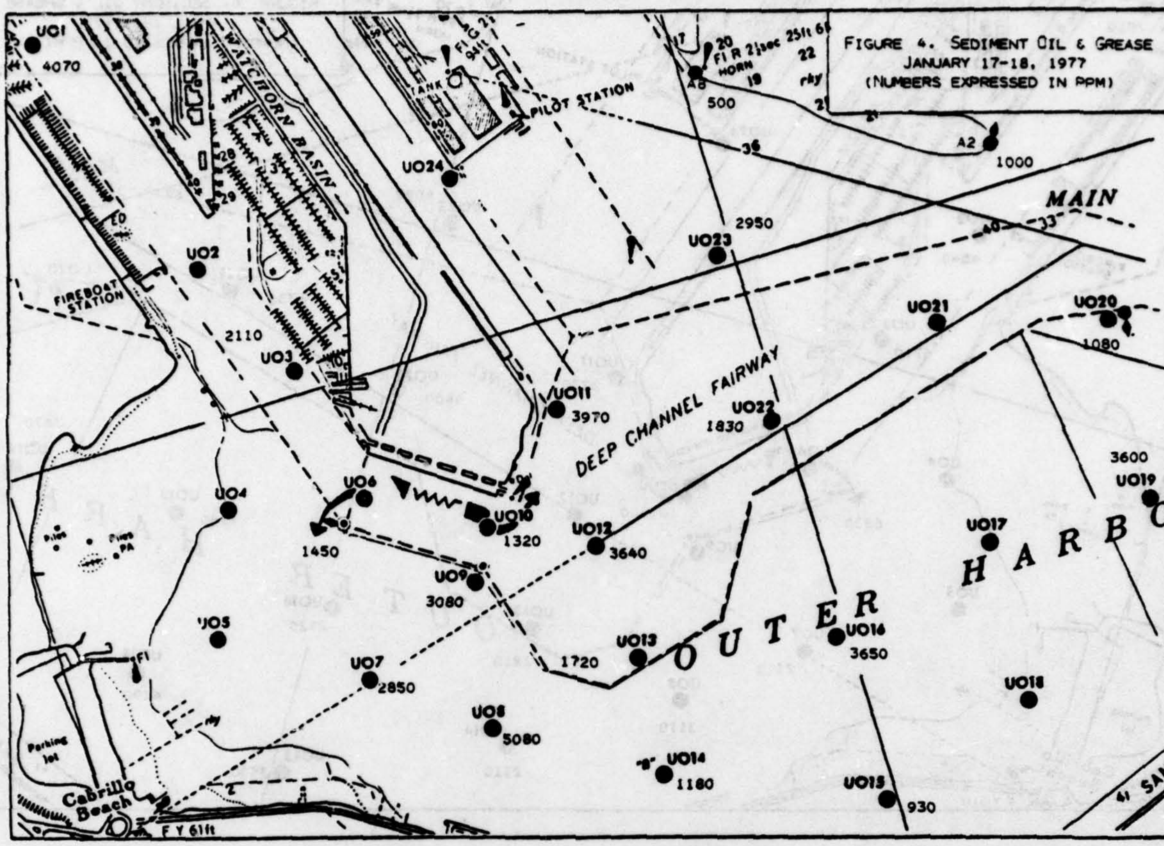


FIGURE 4. SEDIMENT OIL & GREASE
JANUARY 17-18, 1977
(NUMBERS EXPRESSED IN PPM)

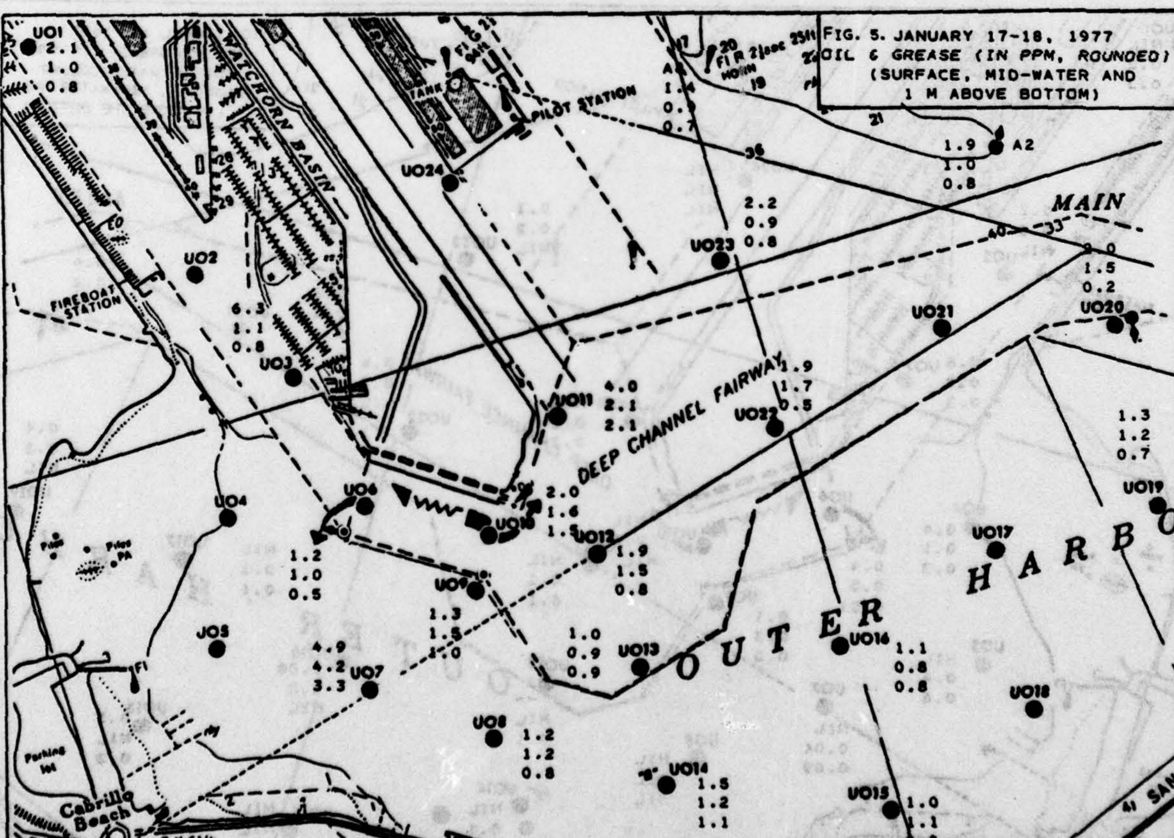


FIG. 5. JANUARY 17-18, 1977
OIL & GREASE (IN PPM, ROUNDED)
(SURFACE, MID-WATER AND
1 M ABOVE BOTTOM)

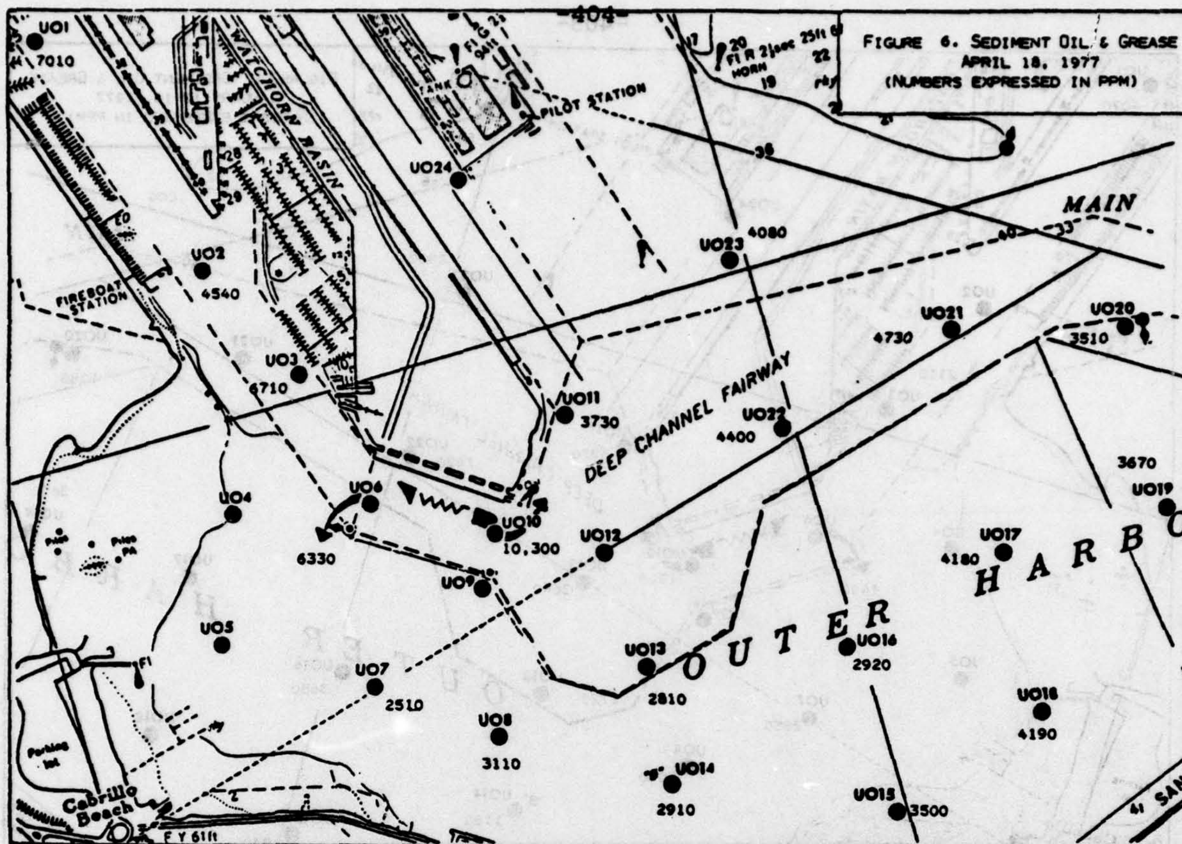


FIGURE 6. SEDIMENT OIL & GREASE
APRIL 18, 1977
(NUMBERS EXPRESSED IN PPM)

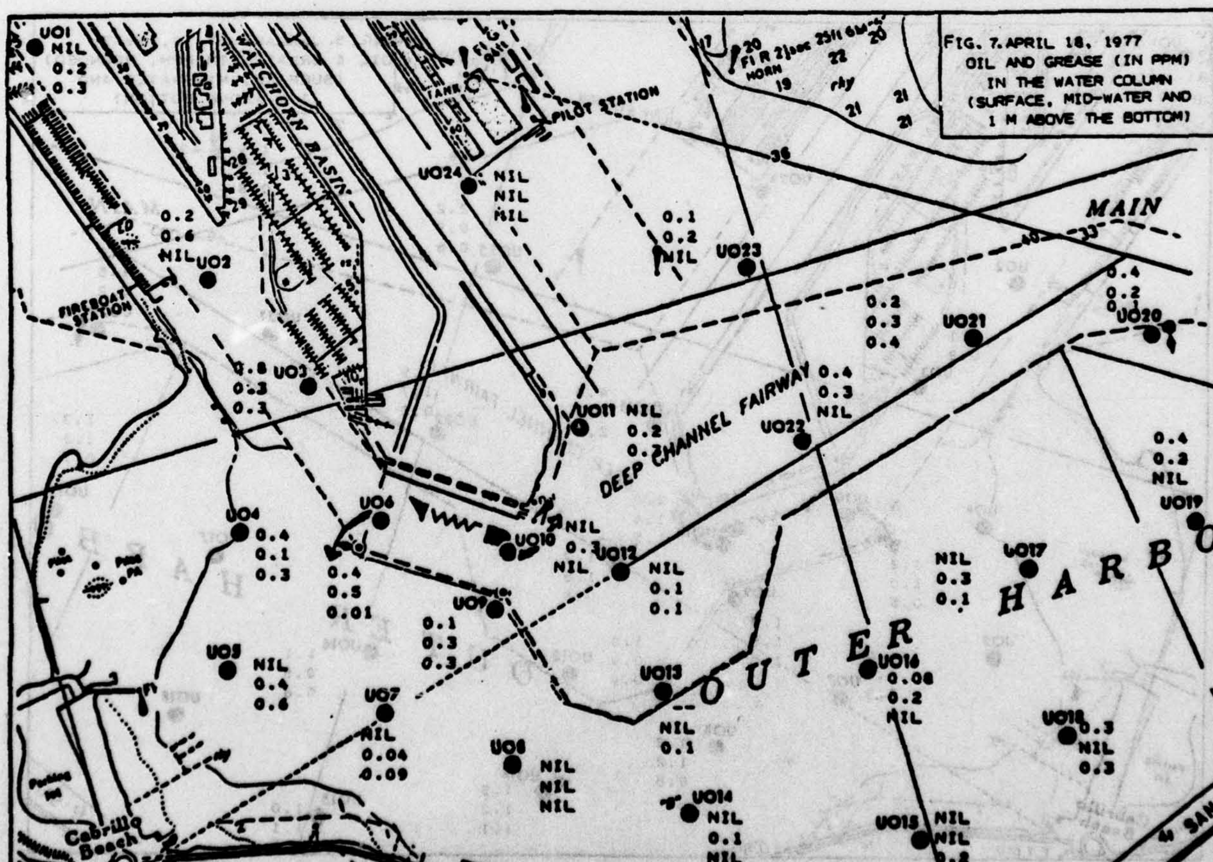


FIG. 7. APRIL 18, 1977
OIL AND GREASE (IN PPM)
IN THE WATER COLUMN
(SURFACE, MID-WATER AND
1 M ABOVE THE BOTTOM)

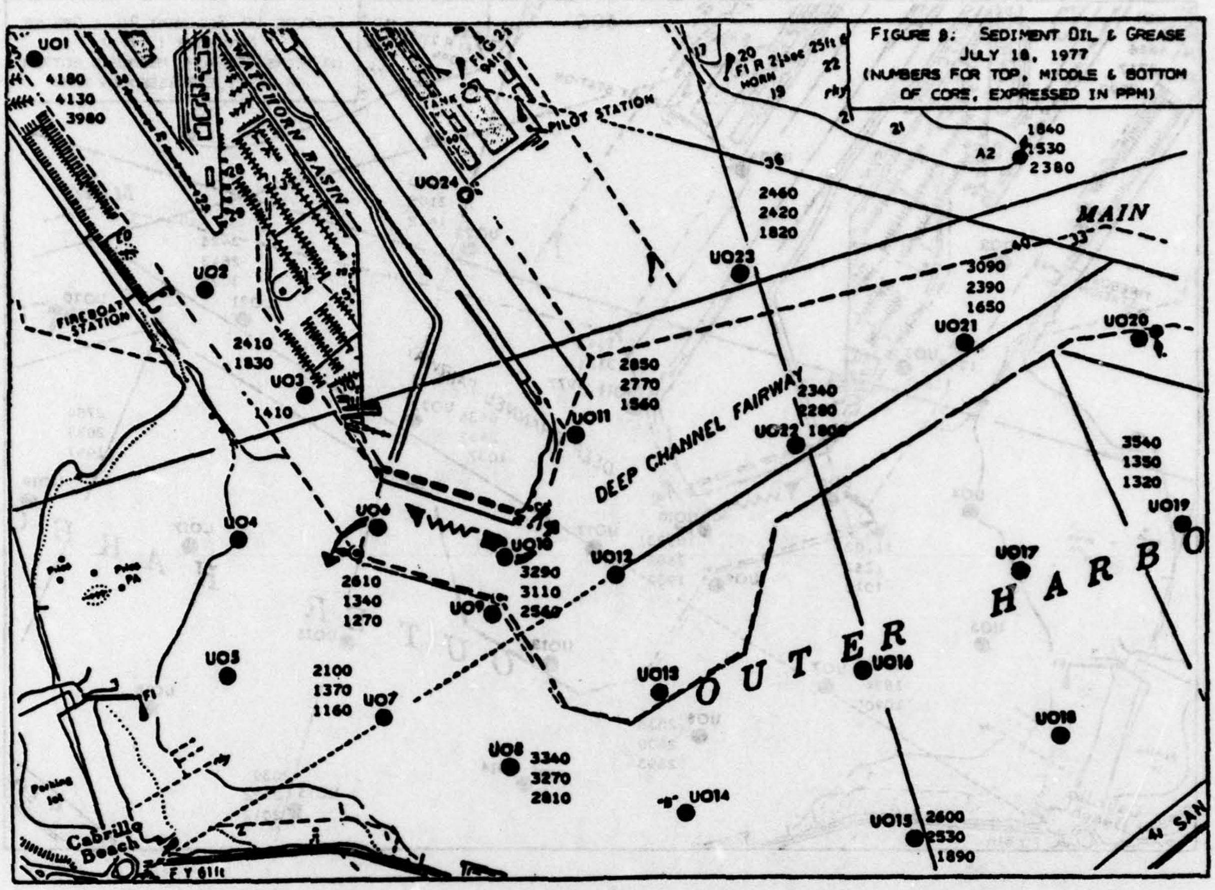


FIGURE 8: SEDIMENT OIL & GREASE JULY 18, 1977 (NUMBERS FOR TOP, MIDDLE & BOTTOM OF CORE, EXPRESSED IN PPM)

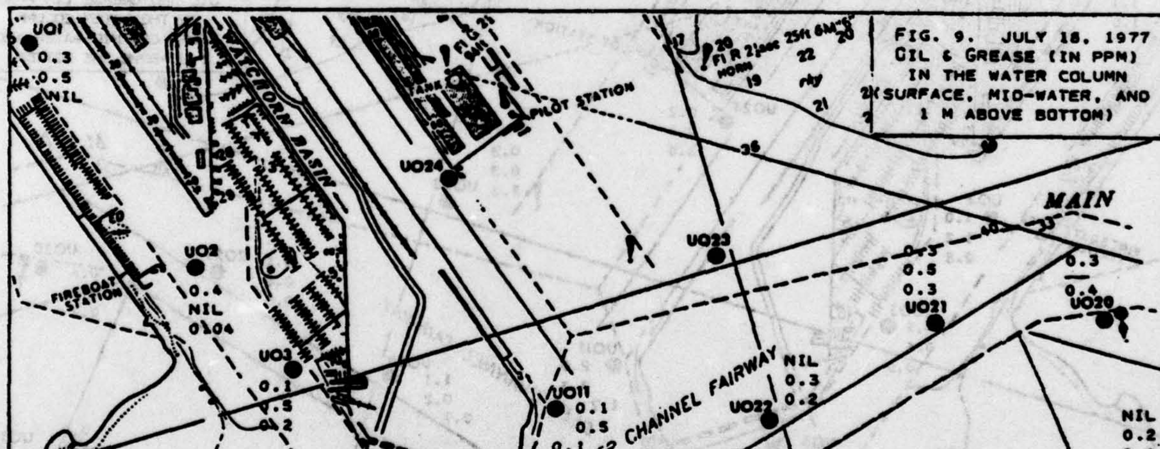


FIG. 9. JULY 18, 1977 OIL & GREASE (IN PPM) IN THE WATER COLUMN (SURFACE, MID-WATER, AND 1 M ABOVE BOTTOM)

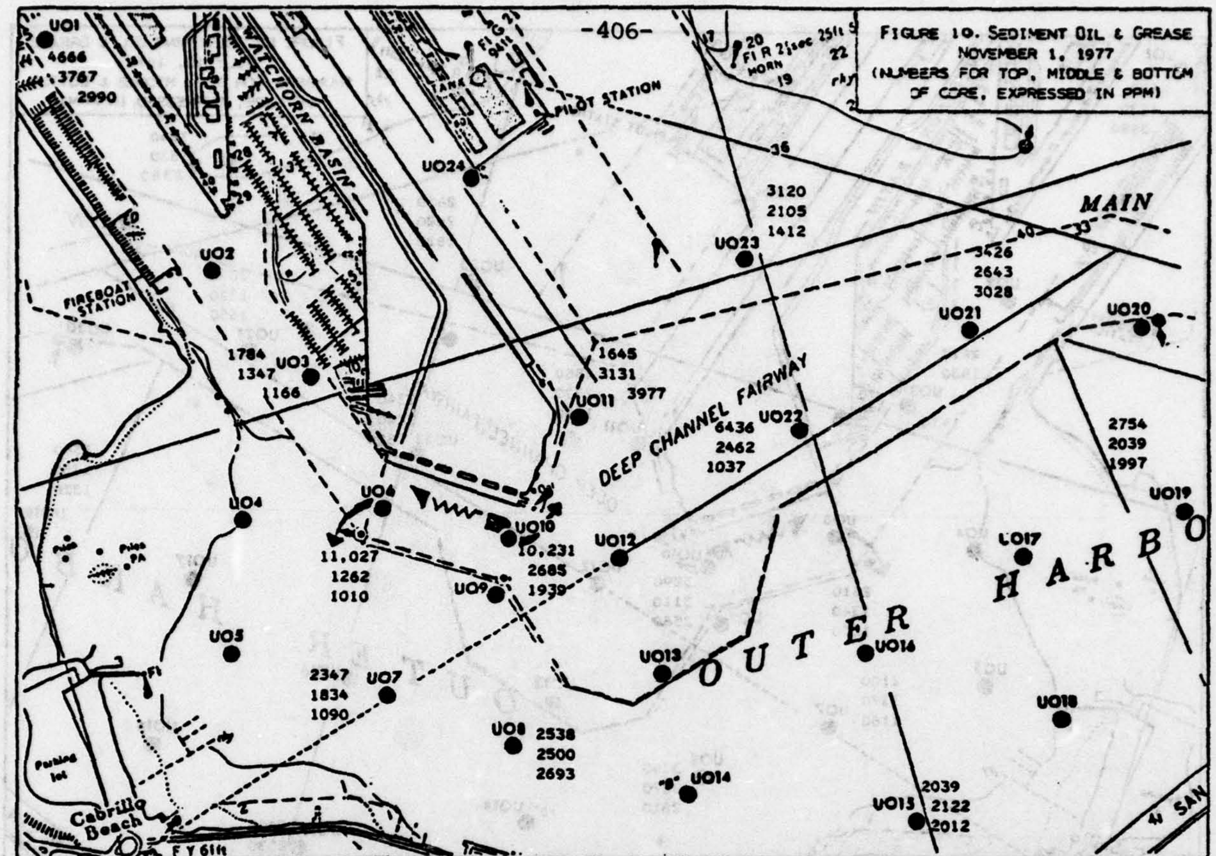


FIGURE 10. SEDIMENT OIL & GREASE
NOVEMBER 1, 1977
(NUMBERS FOR TOP, MIDDLE & BOTTOM OF CORE, EXPRESSED IN PPM)

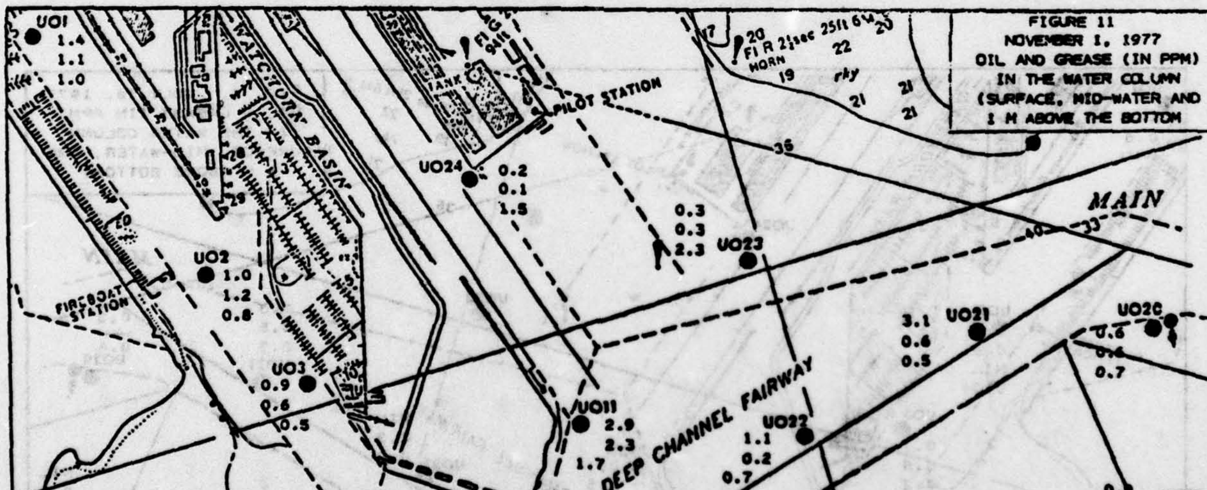


FIGURE 11
NOVEMBER 1, 1977
OIL AND GREASE (IN PPM)
IN THE WATER COLUMN
(SURFACE, MID-WATER AND 1 M ABOVE THE BOTTOM

except for the shallow stations nearest the breakwater. Concentrations in the water column were also higher at most stations (Figure 11).

Reconstruction of the pier involved pile driving and barge operations at the site. In spite of the clean-up efforts to remove the pool, it was impossible to remove all of the residue.

The jelly-like blobs that were scattered across the bottom originally weathered to some extent. However, on warm days tiny blobs would rise to the surface, where they dissolved in the sunlight into flat slicks. The vibration of the pile driver also caused blobs to rise to the surface and oil slicks were found daily on the nearby beaches. Weather in the 80-90°F range also occurred into December, 1977.

April, 1978. The first ship to stop at the reconstructed dock did so as a test, with U.S. Coast Guard and Los Angeles Harbor Department as observers. Due to propeller wash, an estimated two barrels of oil rose to the surface, which was boomed off for recovery. Since the pier is a public facility some 30 years old, under lease by the Harbor Department to Union Oil, it cannot be stated that all oil accumulated in the vicinity of the pier was a result of the *Sansinena* incident. Oil slicks are not uncommon near Navy facilities (near station UO2), around the marinas (UO3), and at the boat launching ramp at Cabrillo Beach.

For further detail on oil and grease surveys and a review of the literature on the effects of Bunker C fuel on marine life, see Soule and Oguri (1978).

BIOLOGICAL EFFECTS OF THE SANSINENA INCIDENT

The effects on the marine biota of the *Sansinena* explosion and spillage of Bunker C fuel were evaluated by examining various parameters of the primary producers at the base of the food chain, and the consumer organisms in the ecosystem of the Los Angeles-Long Beach Harbor. These data were compared with those of previous years, especially 1973 and 1974 (AHF, 1976).

Phytoplankton Productivity and Chlorophyll *a*

While sampling was very difficult in the first month after the incident in the area of the spill because of containment efforts, it was possible to make some comparisons of the phytoplankton productivity and chlorophyll *a*. Sampling

had been carried out at the regular HEP stations in the vicinity on December 1, 1976 as part of the monthly program, supported at that time partially by the Southern California Gas Company and the Sea Grant Program. The stations of this series that are near the site of the incident are stations A2, A8 and A9. Station A10 was not sampled on that date. These stations are shown in Figure 1.

Station A9 is beside the channel marker buoy where the Sansinena docked; this station became identified as U09 for the oil study. It was not possible to get to the buoy itself, so samples were taken just outside the boom ("sea curtain") to the east of A9. Station A10 is at the entry of the Holiday Harbor Marina, and was close to U03, which was located in the center of the West Channel rather than to the side of the marina. Routine measurements had not been carried out at A10 since the 1973-1974 studies, but it had been used intermittently for a phytoplankton sampling site for another research study.

Stations A8 and A2 are located across the Los Angeles Main Channel and thus should have escaped the flow of Bunker C on the bottom. These two stations thus constituted comparative locations for examining possible effects from the oil nearer the site of the spill.

Primary productivity measurements were carried out using a modification of the method of Steeman Nielsen (1952). In this method radiocarbon ^{14}C as a carbonate is used as a tracer in the photosynthetic conversion of nutrient salts to living material by phytoplankton. Productivity values are expressed as $mgC/hr/m^3$. These values represent the ability of the phytoplankton present, regardless of population size, to synthesize organic material under the conditions prevalent in the waters sampled. The time factor indicates that this is a measurement of a rate at which a biological process is carried out, unlike most values which represent standing crop or the amount of material present at a given time.

The photosynthetic pigments, the chlorophylls, were assessed by spectrophotometric measurement of acetone extracts of the phytoplankton following the method and formulae described by Strickland and Parsons (1968). Chlorophyll values are a measure of the standing crop of the phytoplankton population present at the time and place of sampling. The determination is made on the basis of pigment analysis; the quantity varies among species and cells but is an acceptable measure of the material available to catalyze conversion of non-living material to phytoplankton.

Primary productivity readings at A2 and A8 (Table 2)

were very low in December 1976 prior to the spill on December 17, 1976, and at A9 they were higher but in the low range. Oguri (1976) published tables of values obtained in 1973 and 1974 for primary productivity and chlorophyll *a* (Allan Hancock Foundation, 1976).

The values at A8 and A2 of primary productivity and chlorophyll *a* remained stable at their low level (Figure 12) throughout the month of December, through January 5, 1977. The values for productivity at A9 rose slightly and then dropped lower by January. At UO3, the first productivity reading in late December was much higher than the others, but it dropped precipitously by January 5th.

The time of year during which the Sansinena incident occurred coincides with the season of lowest phytoplankton productivity and standing crop. As may be seen in Table 2, the values for December 1976 are quite low with a high value occurring at UO9/A9. A8 and A2 show values more typical of those expected in this season. Following the explosion the data for December 30 are higher than the earlier ones. The only direct comparison for this date in productivity values occurred at UO9/A9. There the increase was moderate. The other values are sharply higher than the earlier values for samples taken from nearby stations. All values recorded to January 5 are low and typical of what is expected for this season. Chlorophyll *a* values were clustered closely for A2, A8 and A10, at 0.84, 0.93 and 1.08 respectively. Initially A9 had a higher reading at 1.54, but dropped to 0.95, close to the other values. Station UO20 was slightly lower than the others. From the chlorophyll *a* data, which show no great changes, it appears that the phytoplankton population did not increase but that the short-lived increase in productivity represents an increase in the rate at which the existing population is producing. This could be triggered by a sudden increase in the availability of a limiting nutrient or growth factor. The nutrient data, discussed below, tend to support this, since these show modest increases, particularly ammonia. However, the nutrient levels remained elevated and productivity did not. Productivity and chlorophyll *a* showed a rising slope for the regular sampling on February 5, 1977 (Figure 12), perhaps showing recovery from stress.

Nutrients

Nutrient levels in the entire harbor were measured in 1973 and 1974 (AHF, 1976). Nitrite, nitrate and ammonia values were determined for A stations on December 1, 1976 prior to the explosion, and at the Union Oil stations shortly afterward.

Nitrite. Nitrite levels generally are at maximum in June-

Table 2. **Comparison of Primary Productivity and Chlorophyll A Before and After Bunker C Spill, on December 17, 1976.**

	1 Dec	23 Dec	30 Dec	5 Jan	18 Jan
PRODUCTIVITY					
nearest Sansinena					
A9 =UO9	3.45		4.54	1.92	
A10=				1.29	
near UO3			6.63		
across main channel					
A8	0.72			0.98	
A2	0.93				
n. side of fairway					
UO23			4.26	0.94	
s. side of fairway					
UO21			1.84		
UO20			2.54		
CHLOROPHYLL A					
nearest Sansinena					
A9	1.54		0.95	1.01	
A10=	1.08				
near UO3			0.95		
across main channel					
A8	0.93			0.95	
A2	0.84			0.99	
n. side of fairway					
UO23					
s. side of fairway					
UO21					
UO20			0.75		

Table 3. **Comparison of Nutrients Before and After Bunker C Spill, on December 17, 1976.**

	1 Dec	23 Dec	30 Dec	5 Jan	18 Jan
NITRITE					
nearest Sansinena					
A9 =UO9	0.21		0.19	0.22	0.23
A10=				0.28	
near UO3		0.20	0.22		0.13
across main channel					
A8	0.19			0.18	
A2	0.16			0.11	0.26
n. side of fairway					
UO23			0.20		0.15
s. side of fairway					
UO21			0.14		
UO20			0.14		0.14
NITRATE					
nearest Sansinena					
A9=UO9	4.65		6.42	6.14	6.30
A10=				5.45	
near UO3		6.82	5.18		6.71
across main channel					
A8	3.98			4.20	
A2	2.02			3.29	5.11
n. side of fairway					
UO23			5.42		4.85
s. side of fairway					
UO21			5.70		
UO20			5.87		4.50
AMMONIA					
nearest Sansinena					
A9=UO9	1.93		4.86	7.23	
A10=				8.34	
near UO3		2.93	7.24		
across main channel					
A8	2.87			6.57	
A2	1.16			2.76	
n. side of fairway					
UO23			5.41		
s. side of fairway					
UO21			6.63		
UO20			8.78		

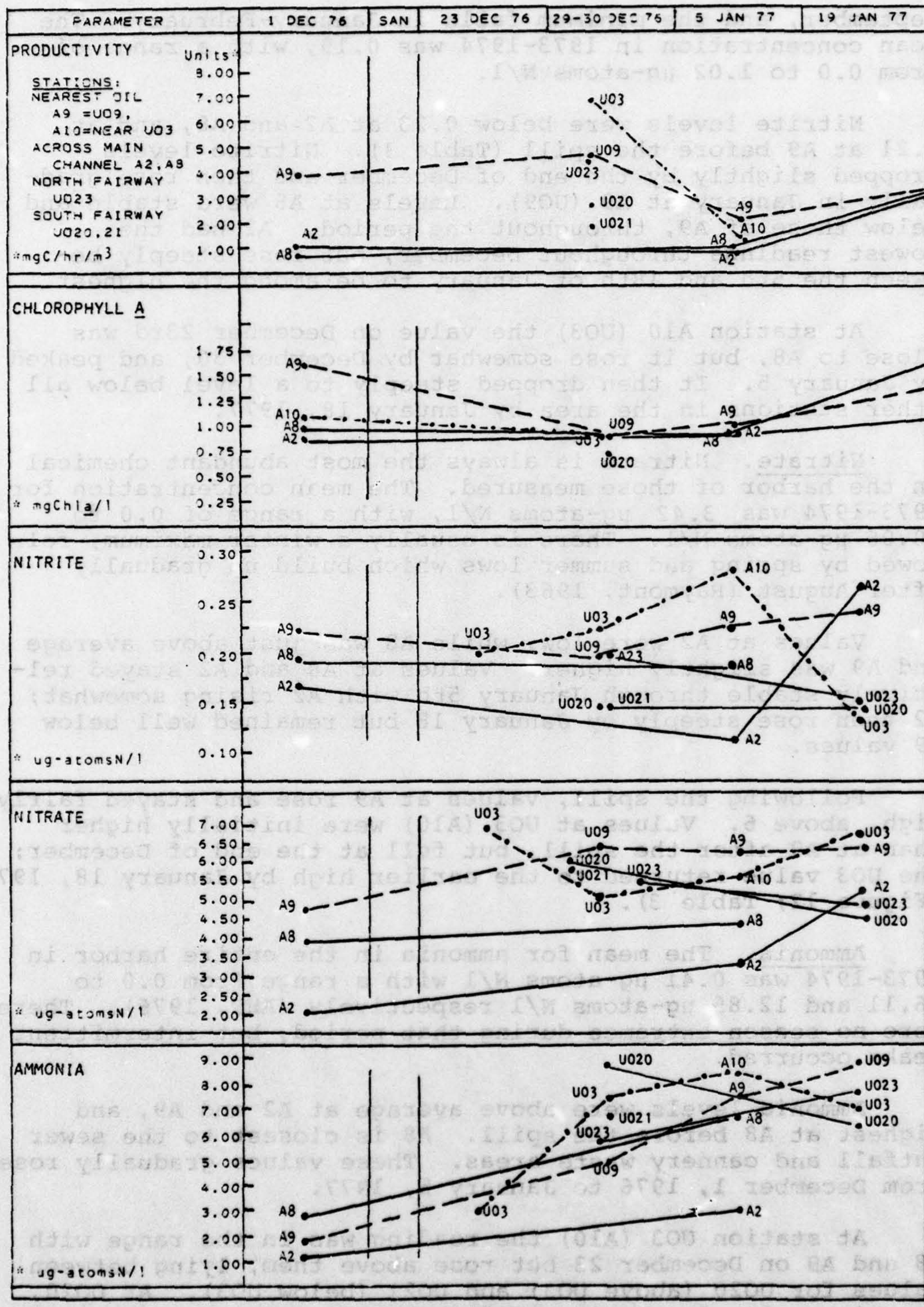


FIGURE 12. COMPARISON OF PHYTOPLANKTON AND NUTRIENTS BEFORE AND AFTER THE SANSINENA SPILL.

September, and the minimum falls in January-February. The mean concentration in 1973-1974 was 0.19, with a range of from 0.0 to 1.02 μg-atoms N/l.

Nitrite levels were below 0.20 at A2 and A8, and at 0.21 at A9 before the spill (Table 3). Nitrite levels dropped slightly by the end of December and then rose gradually in January at A9 (UO9). Levels at A8 were stable and below those of A9, throughout the period. A2 had the lowest readings throughout December, but rose steeply between the 5th and 18th of January to be among the highest.

At station A10 (UO3) the value on December 23rd was close to A8, but it rose somewhat by December 30, and peaked by January 5. It then dropped steeply to a level below all other stations in the area by January 18, 1977.

Nitrate. Nitrate is always the most abundant chemical in the harbor of those measured. The mean concentration for 1973-1974 was 3.42 μg-atoms N/l, with a range of 0.0 to 10.06 μg-atoms N/l. There is usually a winter maximum, followed by spring and summer lows which build up gradually after August (Raymont, 1963).

Values at A2 were low, while A8 was just above average and A9 was slightly higher. Values at A8 and A2 stayed relatively stable through January 5th with A2 rising somewhat; A2 then rose steeply by January 18 but remained well below A9 values.

Following the spill, values at A9 rose and stayed fairly high, above 6. Values at UO3 (A10) were initially higher than at A9 after the spill, but fell at the end of December; The UO3 value returned to the earlier high by January 18, 1977 (Figure 12; Table 3).

Ammonia. The mean for ammonia in the entire harbor in 1973-1974 was 0.41 μg-atoms N/l with a range from 0.0 to 26.11 and 12.85 μg-atoms N/l respectively (AHF, 1976). There were no season extremes during that period, but intermittent peaks occurred.

Ammonia levels were above average at A2 and A9, and highest at A8 before the spill. A8 is closest to the sewer outfall and cannery waste areas. These values gradually rose from December 1, 1976 to January 5, 1977.

At station UO3 (A10) the reading was in the range with A8 and A9 on December 23 but rose above them, lying between values for UO20 (above UO3) and UO21 (below UO3). At UO20, the high value decreased, as did the UO3 value by January 18.

Summary of Results

It seems clear that drops in productivity and chlorophyll *a* occurred during the first two weeks after the spill at the stations closest to the spill, an adverse effect of unknown duration. Values had risen by February 5, 1977. Nutrient levels peaked well above ambient in the two weeks after the spill in the vicinity. Nitrite rose near the spill and then dropped below ambient by January 18 except at A9. Nitrate remained high closest to the spill site but dropped in the fairway. Ammonia rose and remained high; it was highest nearest the spill.

Although data points were limited prior to the spill, and restricted by cleanup operations and scope of the funded study, the trends appear to be valid.

BENTHIC BIOLOGY

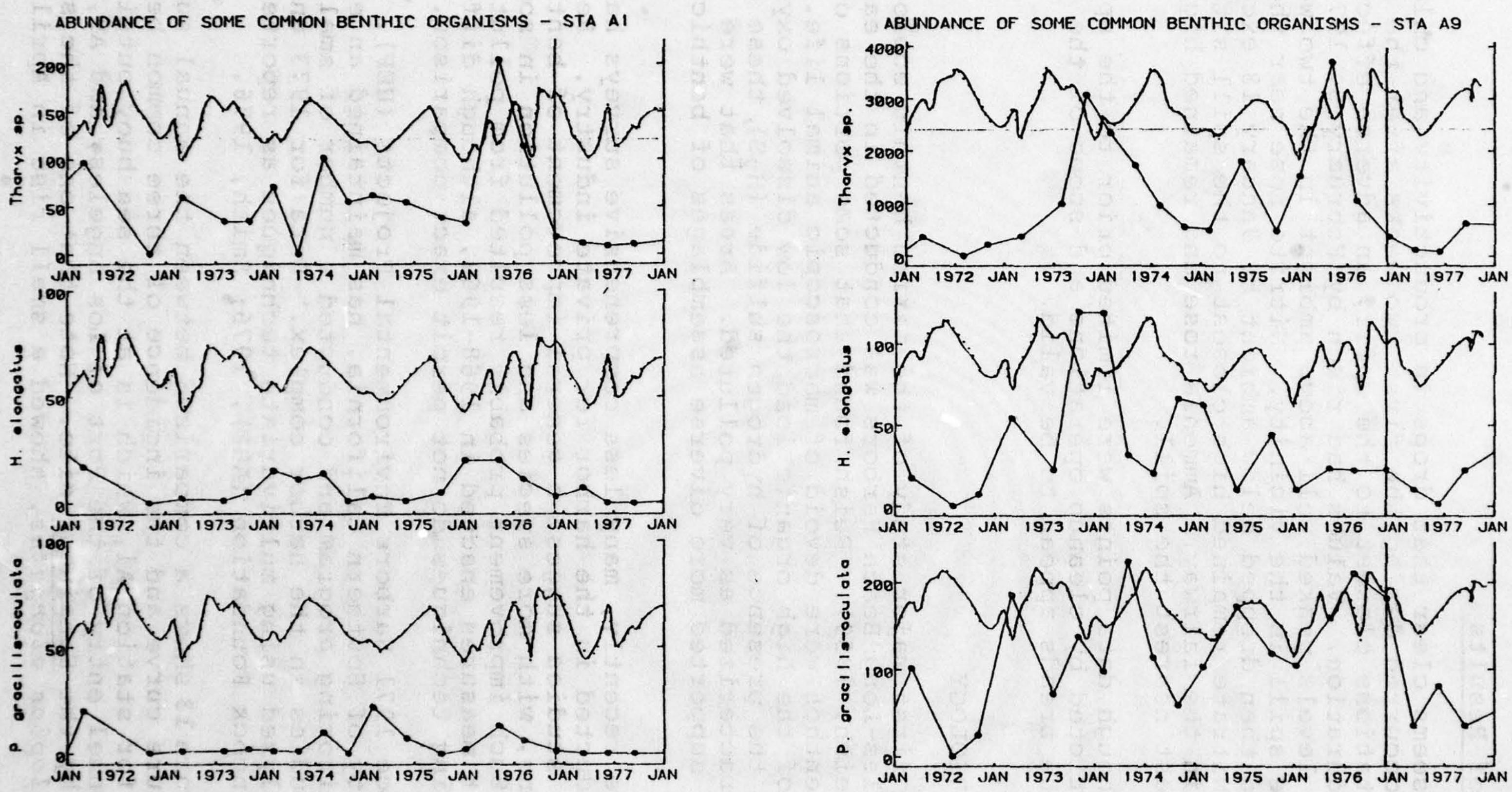
The first major study of the marine benthic ecology of Los Angeles-Long Beach Harbors was conducted in the early 1950s (Reish, 1959). Reish found that some portions of the Harbor benthos were devoid of macroscopic animal life. Because of the high organic load, the low dissolved oxygen (DO), and the presence of hydrogen sulfide (H_2S), these areas were characterized as very polluted. Areas that were less polluted supported more diverse assemblages of benthic species.

More recently, many less comprehensive surveys have been conducted in the harbor for private industry. Results of these studies suggest a general improvement of benthic conditions, with more species and less pollution in some areas. Such improvement probably resulted from pollution abatement measures enacted in 1968-1969, although differences in sampling techniques do not permit exact comparison.

Since 1971 Harbors Environmental Projects (HEP), University of Southern California, has maintained an extensive monitoring program and conducted a number of small-scale studies in the harbor complex. Data for 1973 and 1974 were analyzed using multivariate techniques as reported in Allan Hancock Foundation (AHF), 1976; Smith, 1976.

Figure 13 shows a comparison between the annual surface temperature curve and the incidence of three common benthic species for station A1, which is at the sea buoy outside the main channel entry of the Port of Los Angeles, and A9, located by the Sansinena site. Note that one of the species, *Haploscoloplos elongatus*, showed a small rise in April 1977,

FIGURE 13. ANNUAL SURFACE TEMPERATURE (TOP CURVE) AND ABUNDANCES 1972-1977 AT SEA STATION A1 AND SANSINENA SITE A9. (VERTICAL LINE IS DECEMBER, 1976).



at the sea buoy (A1), but otherwise counts were low during 1977. At A9, all three species dropped in April from December-January levels.

The Sansinena data were analyzed by similar programs and results were translated from the dendrograms and two-way table matrices into maps showing the station groupings according to the interactions of benthic organisms and the abiotic parameters measured.

December 29-30, 1976. Clustering of species into groups to produce an inverse (species) dendrogram did not show significant patterns when compared with previous known harbor sites (AHF, 1976). Dendrograms of the station sites produced separations which at first glance appear to be typical of harbor conditions for the season (Figure 14). In general, inner channel areas are warmer and have less circulation (Groups 4 and 5) while outer harbor stations are expected to show oceanic influence (Groups 1, 2, and 3). However, examination of the two-way table (TWT) showed differences among the groups, based on fairly large gaps in the fauna (Figure 15).

Bar graphs revealed that Group 2 stations had the highest mean and extremes of oil and grease in surface sediments, followed by Group 3 and Group 1, in descending order. There was little difference between the means of Groups 1 and 4 with regard to surface sediment oil and grease, so that some other factor must have influenced the separation. Station U04, in very shallow water, stood alone (Group 5); it is a popular feeding area for birds and might reflect this in the benthic fauna.

Concentrations in sediments for the December 30, 1976 benthic sampling ranged as follows:

Group	Minimum	Maximum	Mean
1	1525	4765	2628
2	3925	7290	5850
3	2815	6890	4820
4	410	5035	2426
5	2155	2155	2155

Surface and bottom waters were sampled for oil and grease in December. The groups defined by the benthic species did not seem to be correlated with the surface measurements, which is not surprising. The range was from 4.2 ppm at station U01, down to 0.1 at station 21, on the channel fairway.

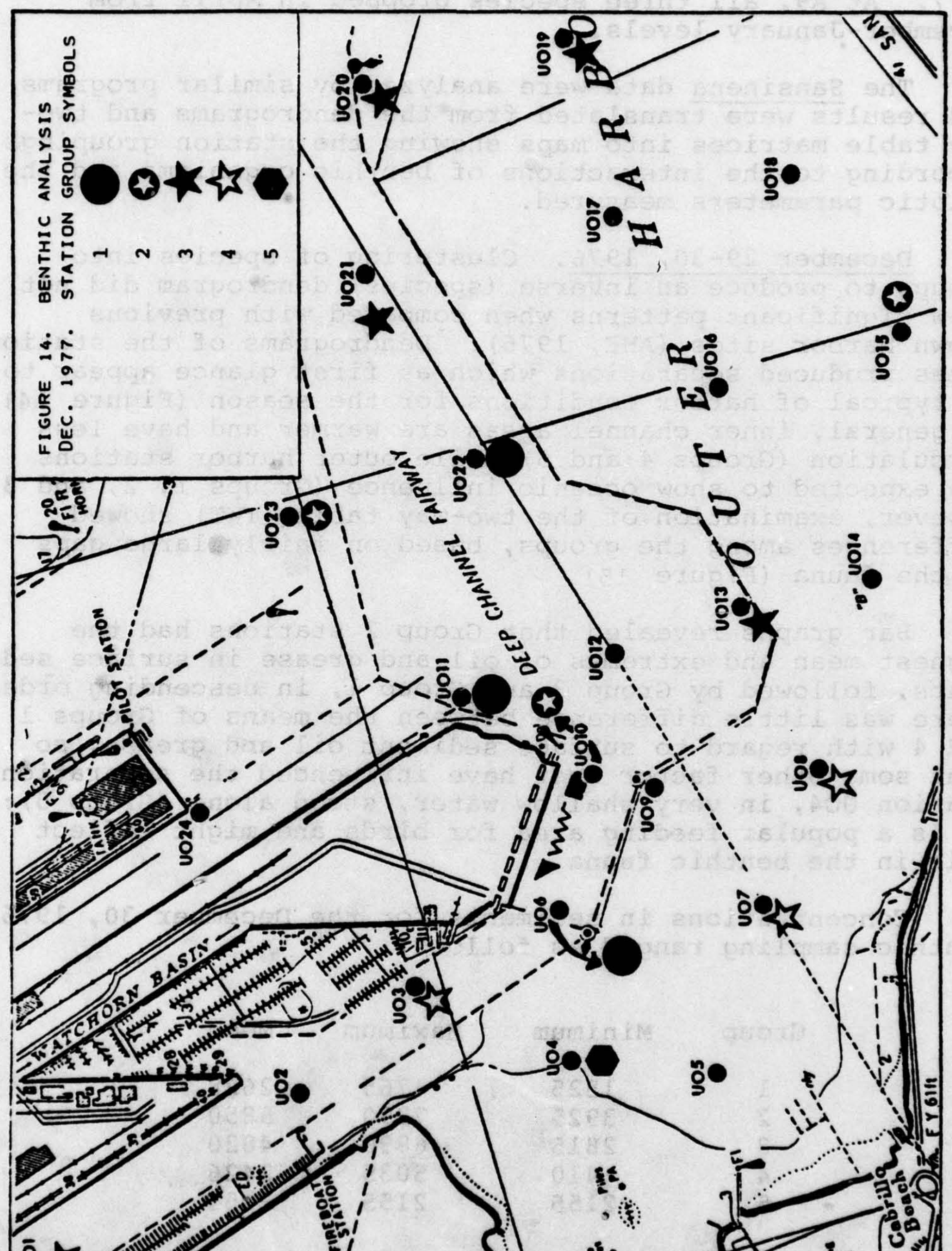
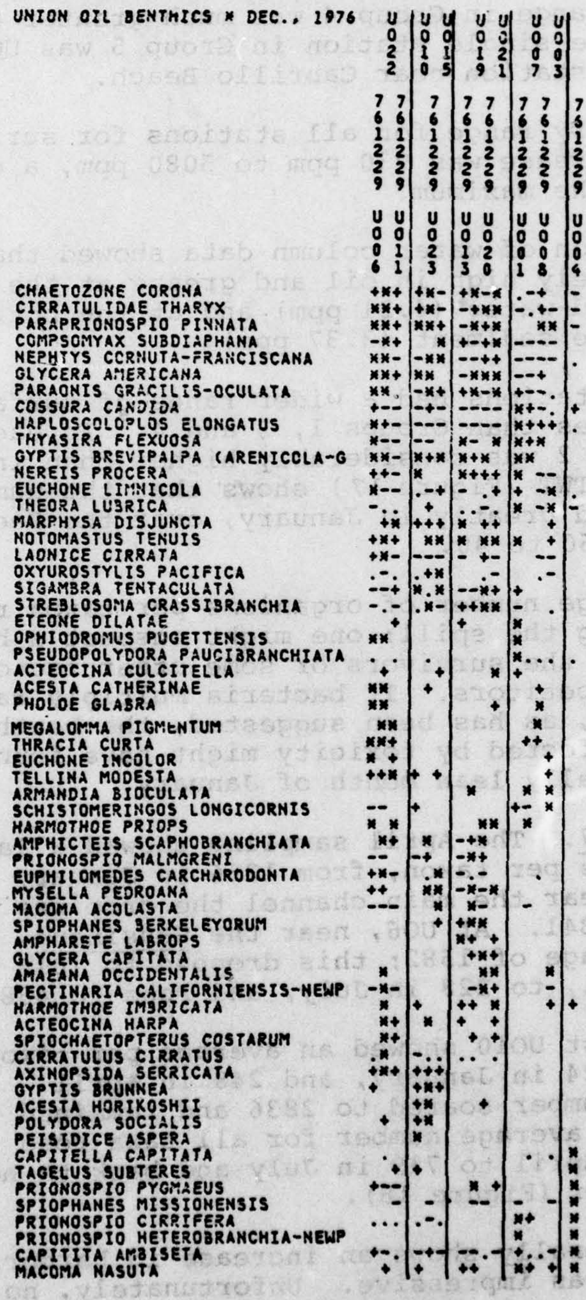


FIGURE 14. DEC. 1977.
BENTHIC ANALYSIS STATION GROUP SYMBOLS
1
2
3
4
5
OUTER HARBOR
DEEP CHANNEL FAIRWAY
WATCHORN BASIN
PILOT STATION
FIREBOAT STATION
Cabrillo Beach
UO1
UO2
UO3
UO4
UO5
UO6
UO7
UO8
UO9
UO10
UO11
UO12
UO13
UO14
UO15
UO16
UO17
UO18
UO19
UO20
UO21
UO22
UO23
UO24

FIGURE 15. SPECIES GROUPS 1 2 3 4 5



January 1977. Examination of January data showed what appeared at first to be the inner slip - outer harbor separation (Figure 16). Group 1 stations were all outer area stations, while Groups 2 and 3 were in the inner slip and near the pier. The ranges and means of these three groups were very similar, in bottom sediment oil and grease. The range in Group 4 was much greater and the mean was higher; the single station in Group 5 was UO7, another shallow water station near Cabrillo Beach.

The January range for all stations for surface sediment oil and grease was 930 ppm to 5080 ppm, a considerable drop in the maximum.

Examination of water column data showed that station UO7 was extremely high in oil and grease at the surface (4.92 ppm), mid-water (4.21 ppm) and at the bottom, one meter above the sediment (3.37 ppm).

Group 2 stations had a wider range of surface and bottom water values than Groups 1, 3 and 4. In each case the mean for Group 2 was considerably higher than in Groups 1, 3 and 4. The TWT (Figure 17) shows that the number of species dropped greatly in January, over the December numbers, from 60 to 40.

The average number of organisms per taxon rose, however, following the spill; one might suspect a biostimulation effect on the survivors or some other factor, such as removal of competitors. If bacteria multiply rapidly following a spill, as has been suggested, the benthic filter feeders not affected by toxicity might have found more to eat in the usually lean month of January.

April 1977. The April sampling showed a large drop in average numbers per taxon, from 1256 in January to 252! At station UO23 near the main channel the drop was from 1865 in January to 341. At UO6, near the Sansinena, December showed an average of 1582; this dropped to 1016 in January, to 361 in April, to 228 in July, and rose to 488 in November.

In contrast UO10 showed an average per taxon of 757 in December, 824 in January, and 248 in April. In July, however, the number soared to 2836 and remained up in November. The average number for all taxa rose from the low of 252 in April to 719 in July and back to normal at 1213 in November (Figure 18).

April generally shows an increase in harbor fauna so that the drop was impressive. Unfortunately, no further studies were possible, so that the trends in 1978 could

not be observed over the UO station pattern. Records for the regular A stations are being taken under contract with the City of Los Angeles.

Classification produced five groups (Figure 19), with Group 1 fairly typical of outer harbor stations and with good diversity and numbers. Station UO15 (Group 5) stood alone, with low species and abundance (Figure 20). Along with station UO21 (Group 2) these two sites had fewer species and lower abundances. They also had the lowest dissolved oxygen and pH, and the highest mean oil and grease in the bottom water. Note that neither of these stations is near the pier. Discriminant analysis separated these two groups only on the basis of depth and salinity values.

July, 1977. Classification produced four groups of sites, largely patterned along the lines of inner slip (Group 1), outer harbor (Group 3) separations (Figure 21). Group 1 had the lowest mean dissolved oxygen and Group 3 the highest. Station UO22 (Group 2) was low in species, and station UO7 (Group 4) was particularly low in clam species (Figure 22).

Groups 2 and 4 were separated at the extremes of depth (deepest and shallowest). Group 4 also had the highest oil and grease value in bottom water but the lowest value in the surface sediment, a very significant separation.

November, 1977. Classification patterns were more definitively separated into outer harbor (Groups 1 and 2) and inner slip (Group 3) stations. There were no really extreme isolates (Figure 23), and the species groups appeared to be more balanced (Figure 24).

Oil and grease levels in the sediments were increased markedly in sediments during the November sampling and showed penetration throughout the 45 cm cores, but in spite of this, populations had mostly recovered. Analysis in July showed that the benthic populations were correlated with oil and grease levels in the water column at one meter above the sediment rather than the oil and grease in the sediment itself. This correlation also suggests that the oil and grease had, for whatever reason, ceased to leach into the water column and therefore toxic substances were no longer affecting the benthic organisms.

Granted that the spill had been cleaned up except for amounts estimated variously from 200 to 4000 barrels, that this may well have migrated to the main channel or been buried by storm-shifted silt. The fact remains that significant reductions occurred in leaching and toxicity and the benthic community recovered in about eleven months.

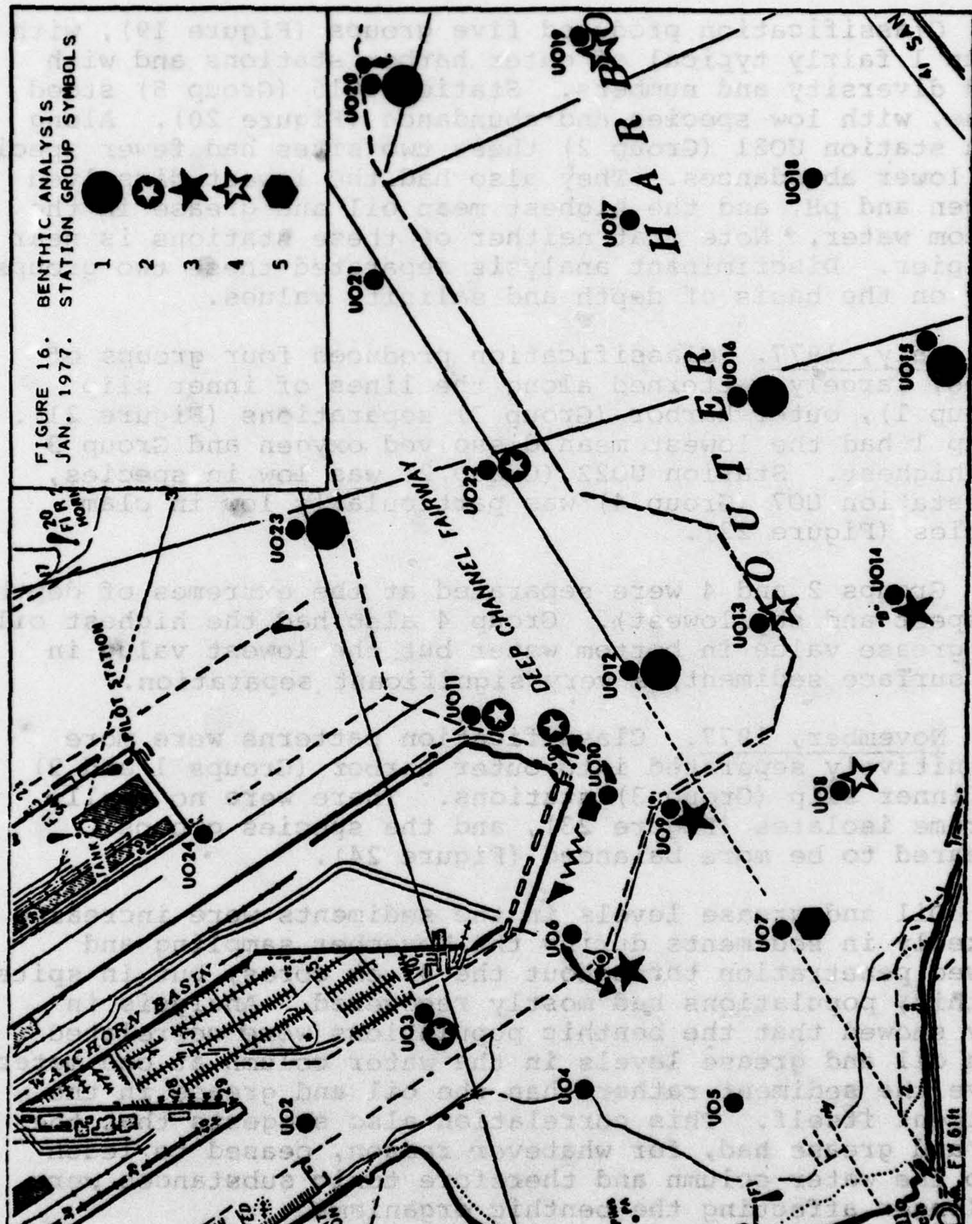


FIGURE 16.
JAN. 1977.
BENTHIC ANALYSIS
STATION GROUP SYMBOLS
1
2
3
4
5
OUTER HARBOR
DEEP CHANNEL FAIRWAY
WATCHORN BASIN
PILOT STATION
FIREBOAT STATION
Cabrillo Beach
UO1
UO2
UO3
UO4
UO5
UO6
UO7
UO8
UO9
UO10
UO11
UO12
UO13
UO14
UO15
UO16
UO17
UO18
UO19
UO20
UO21
UO22
UO23
UO24

UNION OIL BENTHICS * JAN., 1977

FIGURE 17. SPECIES GROUPS

SPECIES GROUPS	1					2				3				4			5
	770117	770117	770117	770117	770117	770117	770117	770117	770117	770117	770117	770117	770117	770117	770117	770117	770117
	U012	U016	U015	U020	U023	U003	U010	U022	U011	U009	U014	U001	U006	U008	U019	U013	U007
AMPHICTEIS SCAPHOBRANCHIATA				*							*						
NOTOMASTUS TENUIS				*							*						
OXYUROSTYLIS PACIFICA				*	-						*						
GYPTIS BREVIPALPA (ARENICOLA-G	-			-	-					-	*						
MARPHYSA DISJUNCTA	*	*	+	+				+	+		*						
GLYCERA CAPITATA						*					*						
HARMOTHOE PRIOPS		*									*						
PARAPRIONOSPIO PINNATA							*	*			*						
PRIONOSPIO MALMGRENI					*						*					*	
COMPSOMYAX SUBDIAPHANA				*	*	*											
OLIVELLA BAETICA				*	*												
LASAEA SUBVIRIDIS		+		-	*												
THRACIA CURTA		*			*												
LAONICE CIRRATA			+		*												
PECTINARIA CALIFORNIENSIS-NEWP				*				*									
PISTA FASCIATA				*													
ACESTA HORIKOSHII			*	*													
GLYCERA AMERICANA	+	+		*										+			
LUCINA NUTTALLI				*								*					
NEREIS PROCERA				*		+	+	*				+					
MYSELLA PEDROANA				*									+				
EUPHILOMEDES CARCHARODONTA		+		*		*	*							+	+		
NEPHTYS CORNUTA-FRANCISCANA	*	*	+	*	*	-	*	*	+	.	*	.		+	.	-	
STREBLOSOMA CRASSIBRANCHIA	-	+	*	*	*	-	-	-				-		-	-	-	
SIGAMBRA TENTACULATA	+	+	*	*	*			*	+	-	+	-				-	
PARAONIS GRACILIS-OCULATA	+	*	*	*	-	+	-	*		*	+	+	.	-	.	-	
CIRRATULIDAE THARYX	+	+	*	*	*	+	-	*	*	+	*	+	-	-	-	-	-
HAPLOSCOLOPLOS ELONGATUS			+	*	-	+		-	*	*	*	+	-	*		-	+
COSSURA CANDIDA	+	*	*		+	*	+	+	+	*	*	*	*	+	.	-	+
CAPITITA AMBISETA	-	+	-	+	*					*	*	-	-	-			.
CHAETOZONE CORONA	-	*	*	-	+	-	+	+	-	+	+		-	*	-		
PRIONOSPIO CIRRIFERA	-							-		-	*	-	*	-			
THEORA LUBRICA										+	-	-	*				
MACOMA NASUTA					-								*				
PSEUDOPOLYDORA PAUCIBRANCHIATA										-		*	*			-	
EUCHONE LIMNICOLA						*	+	*	+	*	+	-	+				
ETEONE DILATAE			*						*								*
PRIONOSPIO PYGMAEUS			+							+							*
CIRRATULUS CIRRATUS	-	+	*					-		.	.						
PHOLOE GLABRA			*														

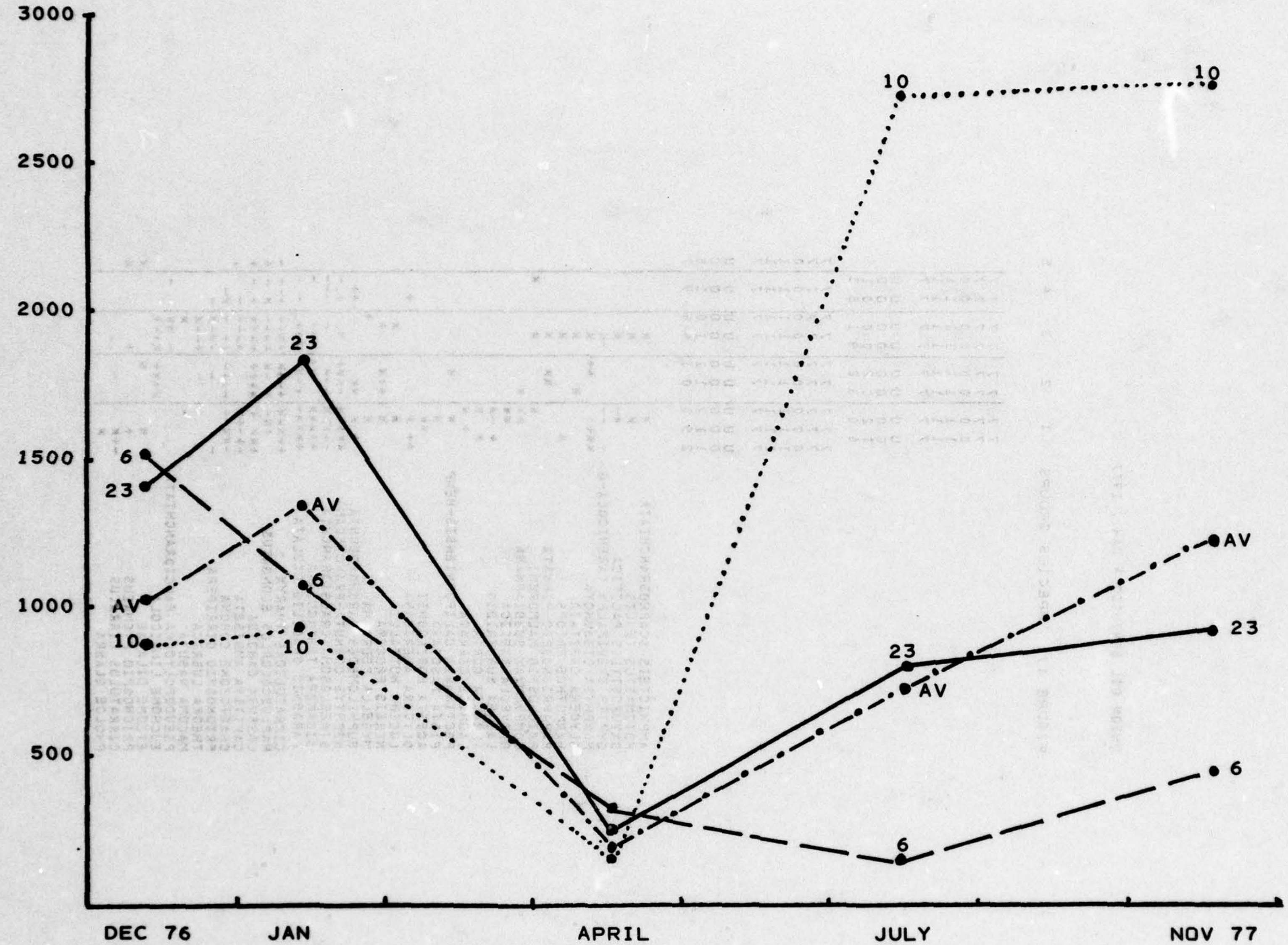


FIGURE 18. $\frac{\text{NUMBER OF SPECIES}}{\text{NUMBER OF INDIVIDUALS}}$ AT STATIONS U06, 10 AND 23, PLUS TOTALS AVERAGED (AV)

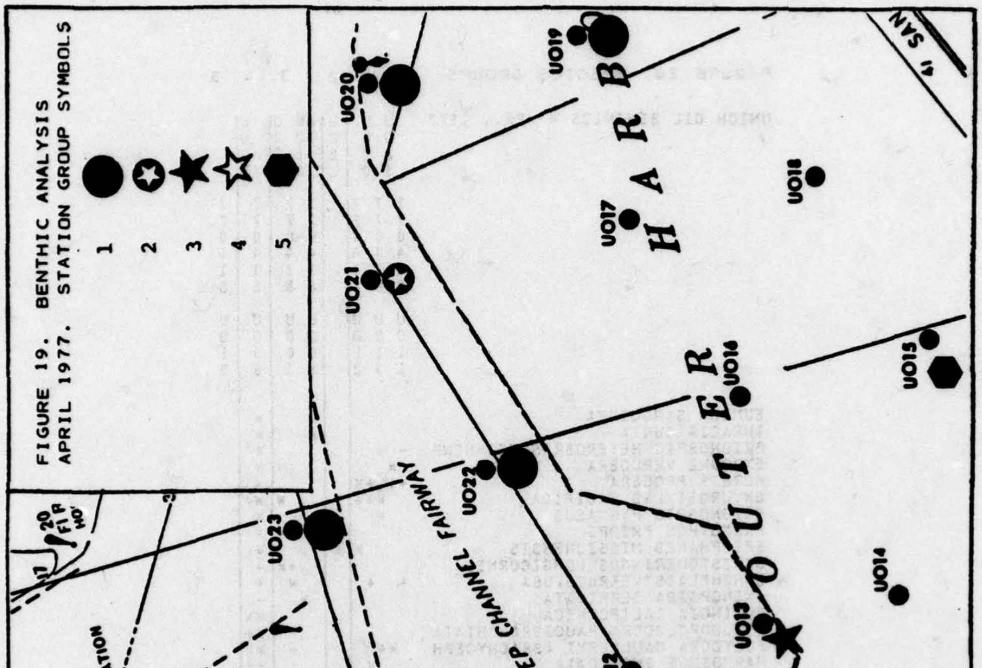


FIGURE 19. BENTHIC ANALYSIS
APRIL 1977.

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FIGURE 20. SPECIES GROUPS             1   2    3  4 5

UNION OIL BENTHICS * APR., 1977      U U |U| U U| U| 
                                     0 0 |0| 0 0| 0| 
                                     2 2 |2| 1 1| 0| 
                                     3 0 |1| 0 3| 7| 

                                    7 7 7| |7 7 |7 |7
                                    7 7 7| |7 7 |7 |7
                                    0 0 0| |0 0 |0 |0
                                    4 4 4| |4 4 |4 |4
                                    1 1 1| |1 1 |1 |1
                                    8 8 8| |8 8 |8 |8

                                    U U U| |U U |U |U
                                    0 0 0| |0 0 |0 |0
                                    1 1 2| |0 0 |0 |1
                                    1 9 2| |8 3 |6 |5

EUMIDA SANGUINEA                         | |*   |* | 
THRACIA CURTA                            | |+   |* | 
PRIONOSPIO HETEROBRANCHIA-NEWP      -    | |    |* | 
EXOGONE VERUGERA                     *   | |    |* | 
NEREIS PROCERA                      ++ +*| |    |* | 
OXYUROSTYLIS PACIFICA                 *++| |   *|* | 
PRIONOSPIO PYGMAEUS                   *  | |    |* | 
HARMOTHOE PRIOPS                         |*|   *|* | 
SPIOPHANES MISSIONENSIS                 *|*|    |* | 
SCHISTOMERINGOS LONGICORNIS              | |  +*|+ | 
STHENELAIS VERRUCULOSA              +  + | |  * |+ | 
AXINOPSIDA SERRICATA                     | | *  |+ | 
CUMINGIA CALIFORNICA                     | |    |**| 
PSEUDOPOLYDORA PAUCIBRANCHIATA           | |..- |*+| 
POLYDORA CAULLERYI (BRACHYCEPH       *+  | |  + |**| 
HARMOTHOE IMBRICATA                    * | |    |++| 
PRIONOSPIO CIRRIFERA                  -+*|-|    |--| 
CAPITITA AMBISETA                   +++*-|.|*-+-|**| 
COSSURA CANDIDA                     -*-*+|-|++-+|**|.
STHENELANELLA UNIFORMIS               -- | |+-- |*-| 
EUCHONE LIMNICOLA                     ...| |+.*.|+.|.
HAPLOSCOLOPLOS ELONGATUS            -- --|-|*.* |+*|:
EUPHILOMEDES CARCHARODONTA          -  +-|+|*+**|* |-
GLYCERA AMERICANA                   **+**|+|  *+|++| 
THEORA LUBRICA                       * --|*| ++-|+*| 
CIRRATULIDAE THARYX                 **+**|+|+*+-|-,|-
NEPHTYS CORNUTA-FRANCISCANA         +--*-|*|+*+-|-.|-
CHAETOZONE CORONA                   +*-.*| |+*.-|. |-
SIGAMBRA TENTACULATA                * ** |+|-* -|  |-
STREBLOSOMA CRASSIBRANCHIA          **+*-| | --+|. | 
PARAONIS GRACILIS-OCULATA           +-***|-|++-+| +|-
PARAPRIONOSPIO PINNATA               +--*| |- *-| +|-
GYPTIS BREVIPALPA (ARENICOLA-G      --*-+|+|-   | -|-
CIRRATULUS CIRRATUS                     *| |   *|  |-
MARPHYSA DISJUNCTA                  *   *| | +  |  |+
COMPSOMYAX SUBDIAPHANA              +*-  |+|---+|  | 
PECTINARIA CALIFORNIENSIS-NEWP      +++*+|*|+ -+|  | 
NOTOMASTUS TENUIS                   ++   |+|  +*|  | 
ACESTA CATHERINAE                   *    | |   *|  | 
THYASIRA FLEXUOSA                     *  | |   *|  | 
AMPHICTEIS SCAPHOBRANCHIATA         -+-- |-|**  | -| 
LAONICE CIRRATA                      * + |+|**  |  | 
MACOMA NASUTA                            | |**+ | *| 
BOCCARDIA BASILARIA                 **   | | *  |  | 
SPIOCHAETOPTERUS COSTARUM           ***  | |**  |  | 
MEGALOMMA PIGMENTUM                      | | ** |  | 
CAPITELLA CAPITATA                  *    | |    | *| 
AMPHARETE LABROPS                     ++*| |    |  | 
MAGELONA PITELKAI                     ** | |    |  | 
STYLATULA ELONGATA                   * + | |    |  | 
MACOMA ACOLASTA                       +  | |*   |  | 
POLYDORA SOCIALIS                      - | |*   |- | 
PHOLOE GLABRA                       ..   |*|    |  | 
PRIONOSPIO MALMGRENI                ++ + |*|    |  | 
MYSELLA PEDROANA                    +- * |+| -  |  | 
PISTA FASCIATA                           |*| *  |  | 
ARMANDIA BIOCULATA                       |*|    |* |*
SPIOPHANES BERKELEYORUM              *   |*|    |  |*
```

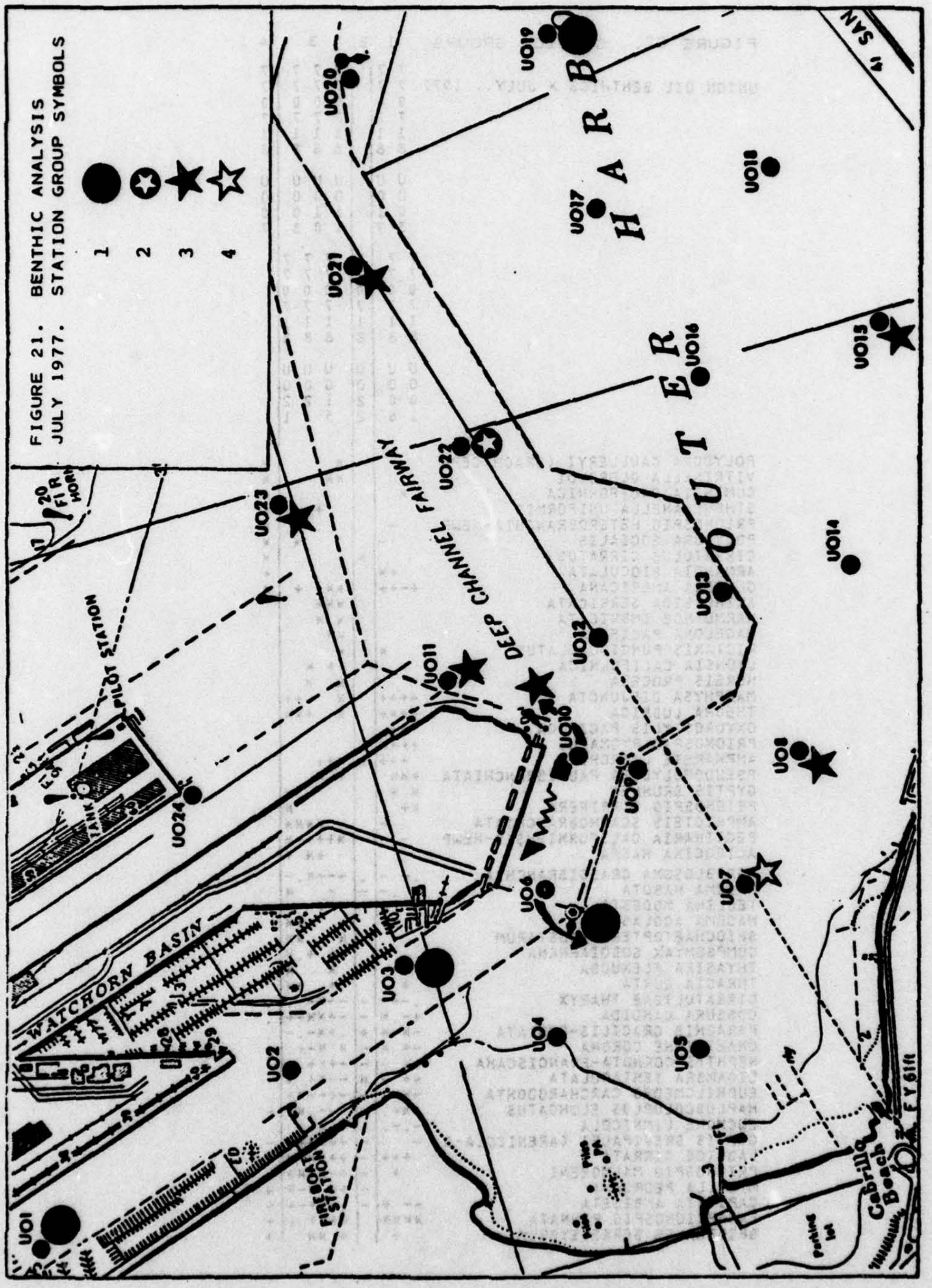


FIGURE 21. BENTHIC ANALYSIS
JULY 1977. STATION GROUP SYMBOLS

FIGURE 22. STATION GROUPS 1 2 3 4

UNION OIL BENTHICS * JULY., 1977

	1	1	1	1	2	3	3	3	3	3	3	4
	770718 U001	770718 U003	770718 U006	770718 U019	770718 U022	770718 U011	770718 U015	770718 U010	770718 U023	770718 U008	770718 U021	770718 U007
POLYDORA CAULLERYI (BRACHYCEPH						*						*
VITRINELLA OLDROYDI						*	*					*
CUMINGIA CALIFORNICA		*										*
STHENELANELLA UNIFORMIS								+				*
PRIONOSPIO HETEROBRANCHIA-NEWP			-					.				*
POLYDORA SOCIALIS				-						*		*
CIRRATULUS CIRRATUS					*							*
ARMANDIA BIOCULATA			+	*								+
GLYCERA AMERICANA	+	-	+	+		+	*			+		*
AXINOPSIDA SERRICATA						*	*	*				
HARMOTHOE IMBRICATA						*		*				
MAGELONA PACIFICA						*	*					
RICTAXIS PUNCTOCAELATUS				*		*						
LYONSIA CALIFORNICA						+	+		*			
NEREIS PROCERA						*			*			
MARPHYSA DISJUNCTA	+	+	+	+		*				+	+	
THEORA LUBRICA	+	*	*	+		*			+	*	*	
OXYUROSTYLIS PACIFICA		*	+									
PRIONOSPIO PYGMAEUS	+	+	+	*								
AMPHARETE LABROPS		+	+	+	*	*	+	+				
PSEUDOPOLYDORA PAUCIBRANCHIATA	+	*	*			+		*				
GYPTIS BRUNNEA	*		*								*	
PRIONOSPIO CIRRIFERA	*	+									*	
AMPHICTEIS SCAPHOBRANCHIATA				-		-		*	*	*	*	
PECTINARIA CALIFORNIENSIS-NEWP			-	-		*	+	+	+	-	*	
ACTEOCINA HARPA								+	*		+	
STREBLOSOMA CRASSIBRANCHIA	.	-		-	.	-	-	-	*	.	-	
MACOMA NASUTA			.	-	-		-				*	
TELLINA MODESTA				*				+			*	
MACOMA ACOLASTA				-		-				+	*	
SPIOCHAETOPTERUS COSTARUM						*				*	*	
COMPSOMYAX SUBDIAPHANA						-	+		+	.	*	
THYASIRA FLEXUOSA							*				*	
THRACIA CURTA		+					+			+	*	
CIRRATULIDAE THARYX	.	-	-	-	-	-	-	*	-	-	.	.
COSSURA CANDIDA	+	-	.	*	-	-	+	*	*	-	+	.
PARAONIS GRACILIS-OCULATA	-	*	-	*	+	.	+	*	-	.	-	.
CHAETOZONE CORONA	-	+		*	-	*		*	-	+		
NEPHTYS CORNUTA-FRANCISCANA	+	*		-	-	+	+	*	+		+	-
SIGAMBRA TENTACULATA	+	+		-	*	-	-	*	+		*	
EUPHILOMEDES CARCHARODONTA	-	*			-	-	+	-	-	*	+	
HAPLOSCOLOPLOS ELONGATUS	+	*	+	.	-		-	-	.	*	*	-
EUCHONE LIMNICOLA	-	.	-	.	.			*	.	-		
GYPTIS BREVIPALPA (ARENICOLA-G	-				-	+	-	+	*	+	*	-
LAONICE CIRRATA		+	+	+	-	+	+	*	*	+	*	+
PRIONOSPIO MALMGRENI			+		-	+	-	*	+	*	+	-
MYSELLA PEDROANA					-	+	*		*	-	*	*
CAPITITA AMBISETA	-	-		+	-	.	-	*	+	-	+	+
PARAPRIONOSPIO PINNATA	*	*	*	*		*	+	*	+		+	+
SPIOPHANES BERKELEYORUM			+			+		*	*			+

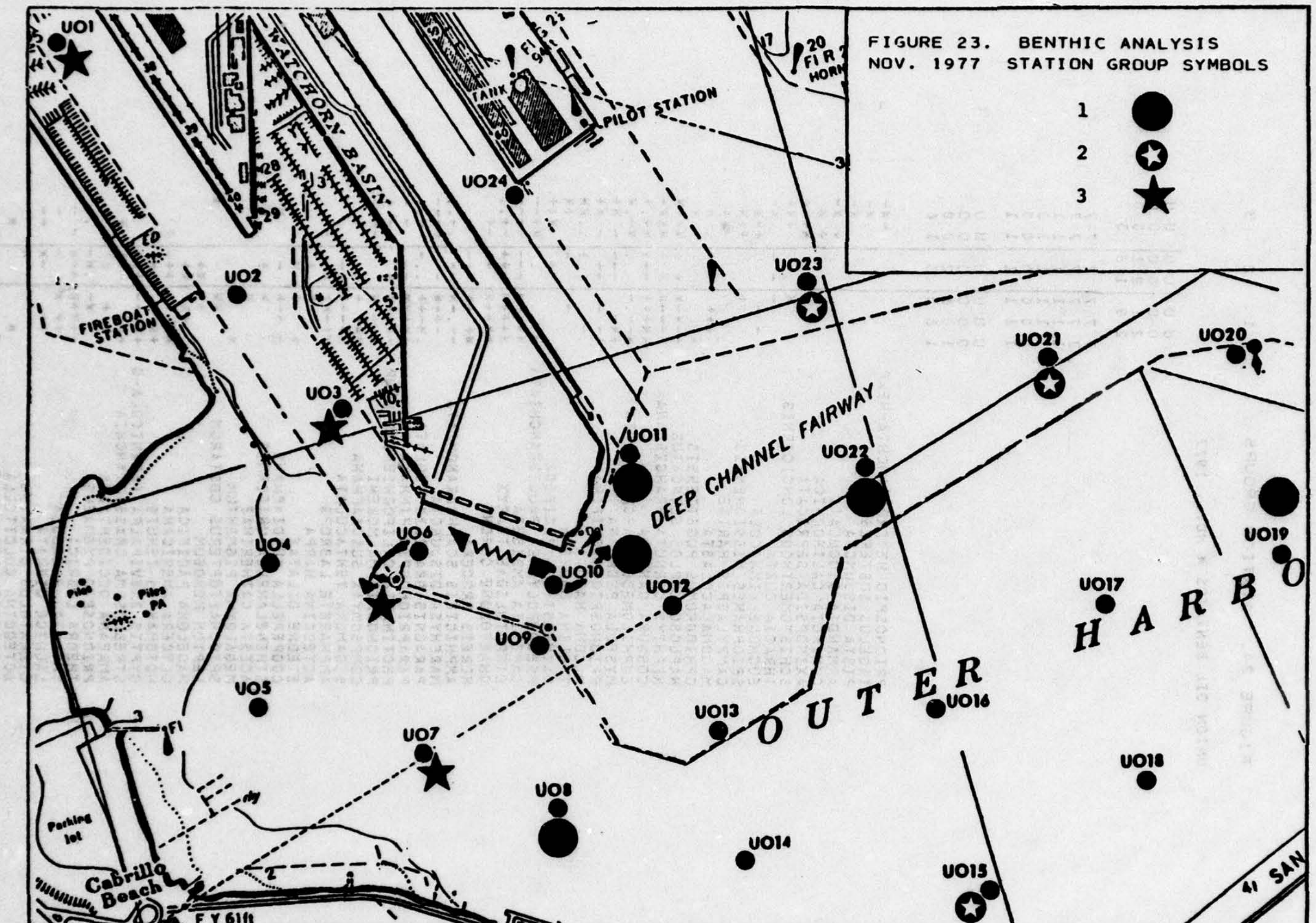


FIGURE 23. BENTHIC ANALYSIS
NOV. 1977 STATION GROUP SYMBOLS

FIGURE 24. STATION GROUPS

UNION OIL BENTHICS * NOV., 1977

STATION GROUPS	1					2			3			
		U0022		U0019		U0021		U0015		U0003		U0007
	771101		771101		771101		771101		771101		771101	
	U0011		U0018		U0010		U0023		U0001		U0006	
PRIONOSPIO HETEROBRANCHIA-NEWP										-	*	-
TAGELUS SUBTERES										.	*	-
PISTA DISJUNCTA			-								*	-
ARMANDIA BIOCULATA									+		*	-
CUMINGIA CALIFORNICA									+		*	
AXINOPSIDA SERRICATA						+			*	+	*	+
SCHISTOMERINGOS LONGICORNIS					*					+	*	+
THRACIA CURTA					-	-		-			*	-
EUCHONE LIMNICOLA		-		-					+	*	*	
SPIOPHANES MISSIONENSIS					+				+	+	*	
CAMPYLASPIS HARTAE										*	*	
MACOMA ACOLASTA		+	+	+				+			*	
OPHIODROMUS PUGETTENSIS	*										*	
HAPLOSCOLOPLOS ELONGATUS	-	-	*	-	*	+		+	*	*	-	*
NEPHTYS CORNUTA-FRANCISCANA	*	-	-	-	*	*		+	*	*	*	-
COSSURA CANDIDA	*	*	+	+	+	-	+	+	*	*	.	+
EUPHILOMEDES CARCHARODONTA	*	-	-	.	-			.	*	-	.	*
MYSELLA PEDROANA	+	*	-			-	-	-	-		*	+
PRIONOSPIO CIRRIFERA	+	-		-		+	+		-		*	+
MACOMA NASUTA	.	-				.		+	.	.	*	*
TELLINA MODESTA				-				-			+	*
OXYUROSTYLIS PACIFICA							+			*	+	+
PSEUDOPOLYDORA PAUCIBRANCHIATA	-		.				.		*	+	-	-
CAPITITA AMBISETA	*	+	.	-	*	-	-	-	-	-	-	-
CIRRATULIDAE THARYX	*	+	+	+	*	-	+	+	-	+	.	.
CHAETOZONE CORONA	*	*	*	+	*		+	-	-	+		
NEREIS PROCERA	*	+		+	*	-	+	-		-		
AMPHICTEIS SCAPHOBRANCHIATA	-	-	.	-	*	-	-		.	-	.	.
MARPHYSA DISJUNCTA		-	+	-	*	-			-	-	-	-
PARAONIS GRACILIS-OCULATA	.	*	-	+	+	.	.	-	-	-	.	.
PARAPRIONOSPIO PINNATA	+	*	+	*	*	-	-			-		-
PECTINARIA CALIFORNIENSIS-NEWP	-	*	-	-	*	*					-	+
PRIONOSPIO MALMGRENI	*	+	-		*				-	-		-
COMPSOMYAX SUBDIAPHANA	*	*	+		+	+				+		
SIGAMBRA TENTACULATA	*	+	-	-	+	*	-			.		
AMPHARETE LABROPS	*	+	-	*	*	-			-			
ACTEOCINA HARPA					*		+					
ETEONE DILATAE	+				+		*					
COOPERELLA SUBDIAPHANA	+		+	-	*		-				*	-
STHENELANELLA UNIFORMIS					*		+				+	
ACESTA CATHERINAE					*	*						
MEGALOMMA PIGMENTUM	*				*							
SPIOCHAETOPTERUS COSTARUM				*	*							+
LEPTON MEROEUM				+		*	+					
MAGELONA PACIFICA			+	*		*	+					
GLYCERA AMERICANA	*		+	+		+	+	+	+			
NOTOMASTUS TENUIS	+	*				*	*	+	+			
GYPTIS BREVIPALPA (ARENICOLA-G	+	*	+	+	-	+	+	+				
STREBLOSOMA CRASSIBRANCHIA	*	+	.		.		+	+	-	*		
AMAEANA OCCIDENTALIS		+		+			*				+	
PRIONOSPIO PYGMAEUS		+		*	-	.	*	-		.	-	
THEORA LUBRICA	-	+	*	+	*	+	-	*	-		-	
THYASIRA FLEXUOSA		+	*		*			-			-	
LAONICE CIRRATA		+	+				-	*		-	-	
CIRRATULUS CIRRATUS					-			*				
ACTEOCINA CULCITELLA		*								*		
ANCISTROSYLLIS HAMATA	*								*			

It is unfortunate that no further sampling could be undertaken to confirm the survival of the benthic organisms as well as the lack of correlation with benthic sediment oil and grease burdens.

Diver-Survey

A cooperative diver survey was led by HEP on December 2, 1977 with participation from the Coast Guard, Corps of Engineers, California Fish and Game, National Marine Fisheries and the Port of Los Angeles. This showed that patches of oil were still present, and a pool of oil was found between UO12 and UO13. A survey made by California Fish and Game personnel in late February, 1978 reported no trace of oil. This followed some severe storms which could have buried the oil or carried it away.

Intertidal studies of Cabrillo Beach and the adjacent breakwater indicated that recovery began on the rocks in March but the algae could not be considered recovered until the spring of 1978. The beach, which previously was dominated by *Lygia*, did not recover a good population until August, 1977 (Soule and Oguri, 1978).

Zooplankton Investigations

Subsequent to the explosion and spill of Bunker C oil from the Sansinena incident, zooplankton sampling was initiated by towing a standard ½ meter, 253μ mesh plankton net at the surface for 5 minute intervals. Sampling was begun within a week after the spill. Following the initial impact, sampling at stations UO1, 3, and 5 was carried out on December 23, 1976, and expanded to ten stations on December 29-30. Special sampling near A9 provided data for the January-March period near the Sansinena. The numbers of species found on December 23 were unusually high, probably as a result of the very high tides during the period.

The following species were found that are rarely present in the harbor.

Eucalanus crassus	*Temora discauddta*
Eucalanus elongatus	*Candacea* sp.
Centropages sp.	*Corycaeus geisbrechti*
Rhincalanus nasutus	*Corycaeus flaccus*
Mecynocera clausi	*Farranula curta*
Lucicutia flavicornis	*Ischnocalanus tenuis*

For comparison, concentrations of dominant zooplankton at regular Harbors Projects stations on December 1, 1976 from the area of the buoy UO9 (=A9) and other nearby harbor stations are given in Text Table 1, along with counts for December 23 and 29-30, 1976.

The abundances of four common species of zooplankton at the sea buoy (A1) outside the harbor and at A9 are plotted in Figure 25 for the period of 1972-1977 against the surface temperature curve. While no winter-spring peaks can be seen at A1 until midsummer, peaks of various sizes occurred at A9. In particular, *Paracalanus parvus* exhibited an intense increase after the spill. Figure 26 gives an expanded scale for the period of November 1976 to December 1977.

The most notable feature following the explosion and spill was the large increase in species diversity of copepods and cladocerans in the area. Prior to the oil spill, UO9 (A9) had been sampled on a regular monthly basis, along with A2, A3 and A8 in the outer harbor across the main channel. On December 29, they were unusually low at UO5. The latter may not be significant, although the station is near the area where oil skimmer boats were bringing wastes ashore at the boat-launching ramp.

The two dominant copepods were *Acartia tonsa* and *Paracalanus parvus*. *Acartia tonsa* appeared to have decreased in concentration from the December 1, 1976 sampling to the post-spill sampling. Mean A2, A8, and A9 *Acartia tonsa* was about 1500/m^3. Mean post-spill *Acartia tonsa* from these areas was about 100/m^3. However, this may not be statistically significant.

Paracalus parvus concentrations in the post-spill samples, particularly UO7 through UO23, was unusually high. Mean *Paracalanus parvus* concentrations in those samples was about 275/m^3, which was considerably higher than it had been since June, 1976. The unusual highs and lows might have been due to the very high tides or to annual variations.

During 1973-1974, mean *Acartia* concentration at A2 was 1800-2400/m^3, 1200-1800 at A9, 600-1200 at A10 and about 600 at A8 (AHF, 1976). At that time mean concentrations of *P. parvus* at A2, A8 and A9 were between 200 and 300/m^3, and below 100 at A10.

It must be noted, however, that at the time of the collection of the first samples subsequent to the spill (stations UO1, 3,5) the plankton collecting crew noted that the copepods showed no apparent activity and appeared dead. Upon sorting these samples, there was no evidence of their death prior to collection by the presence of broken or decomposing bodies. It is possible that the zooplankton was in a state of torpor caused by the presence of the oil spill. While this observation is very subjective, it may be significant nevertheless.

Because of the difficulty with making uniform plankton tows in December through March, these samples were not included in the multivariate analysis and classification programs.

April, 1977. Classification for the period showed four principal station groups (Figure 27). Groups 1 and 2 were predominantly outer harbor, with the exception of station UO2. There were distinct gaps in their species compositions (Figure 28). Groups 3 and 4 occurred nearer to the *Sansinena* site and may reflect the disturbances in the water column due to salvage operations. Group 2, which was unique in species composition, also correlated with the highest pH, highest turbidity and highest primary productivity. Group 3 (stations UO10 and UO22) had the highest mean oil and grease concentrations at the water surface, at the midwater, and at the sediment surface. Group 4 had higher dissolved oxygen levels, but there was considerable overlap.

July, 1977. Four station groups were delineated but the inner slip-outer harbor separation was not apparent (Figure 29). Each group showed distinct gaps in species composition in the TWT (Figure 30). Group 3 had the fewest species. Group 2 separated as having slightly high salinities, a transitory condition. No trends in oil and grease could be discerned.

November, 1977. Three station groups were present in November, and followed the similar pattern seen in benthic groupings for that month. Groups 1 and 2 were outer harbor sites and followed somewhat the tidal gyre in that area. Group 3 were inner slip stations (Figure 31). The TWT (Figure 32) showed Group 3 to have the fewest species. The dissolved oxygen and pH were highest in Group 1 and lowest in Group 3. However, Group 3 had the lowest mean oil and grease levels in surface water, midwater and bottom water (with some overlap in each case so that separation was not definitive). Oil and grease levels in the sediment/surface overlapped extensively and apparently did

not affect the zooplankton. As in the case with the benthic organisms, apparently the toxic effects of the sediment oil and grease were dissipated.

Acknowledgments. The authors would like to acknowledge the assistance of the members of the Harbors Environmental Projects staff, all of whom participated in this effort. Special thanks is extended to R. W. Smith, C. Henry and T.J. Mueller for assistance with computer analysis, and to Ruth Steiger for editorial assistance. Funding has been acknowledged elsewhere; the cooperation of R.J. King of the Union Oil Company was much appreciated. Dr. K.Y. Chen of the USC Environmental Engineering Program provided the oil and grease analysis.

FIGURE 25. ANNUAL SURFACE TEMPERATURES (TOP CURVE) AND ABUNDANCES 1972-1977, SEA STATION A1 AND SANSINENA SITE A9. (NOTE A9 ZOOPLANKTON PEAKS IN JANUARY 1977).

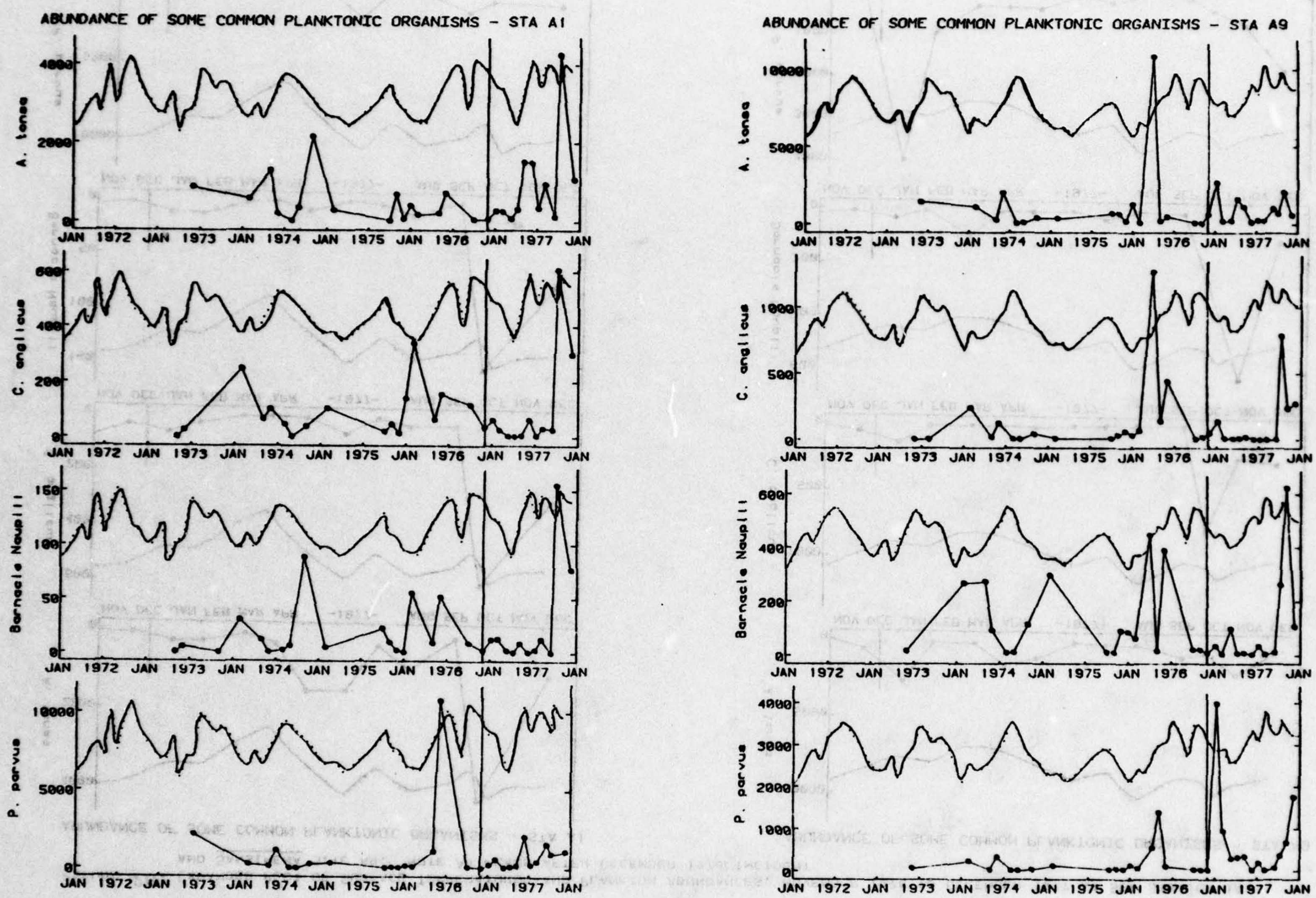
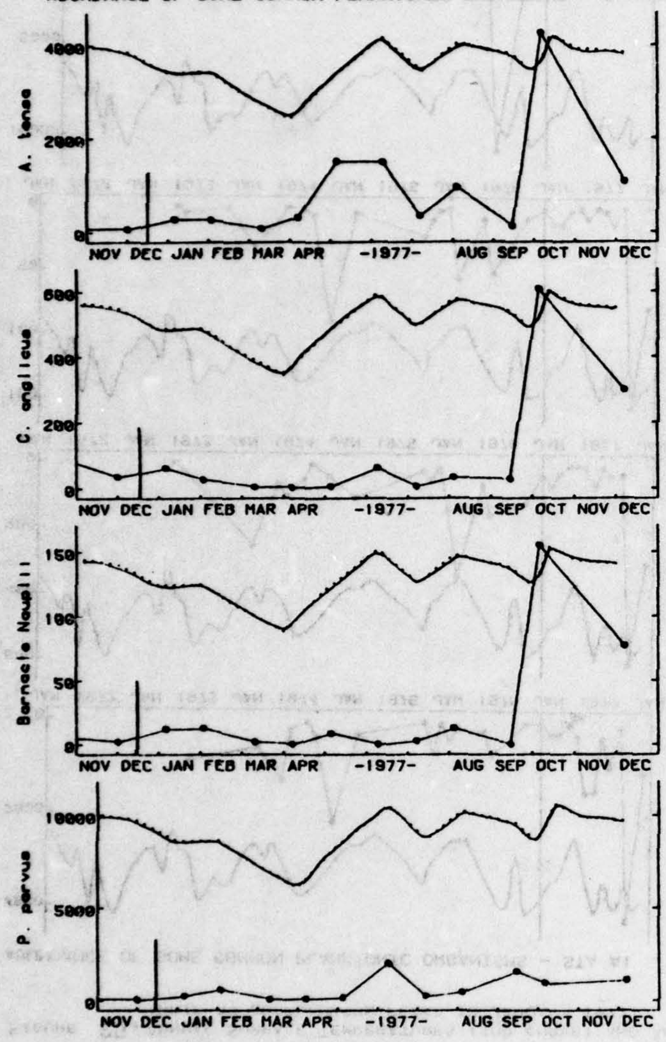
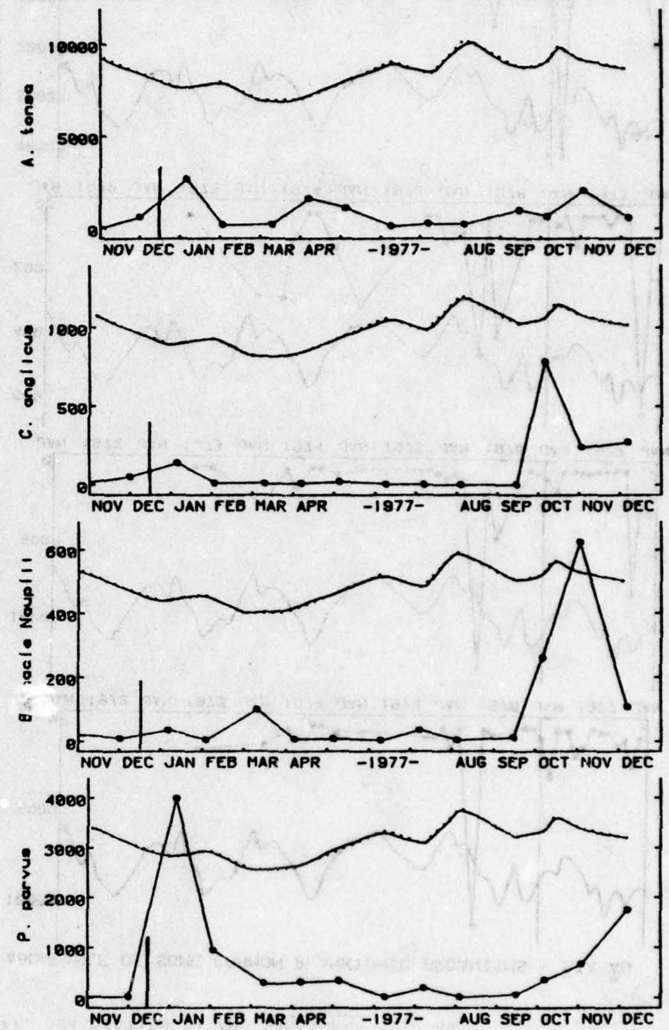


FIGURE 26. EXPANDED PLOT OF SURFACE TEMPERATURES AND PLANKTON ABUNDANCES, NOVEMBER 1976 TO DECEMBER 1977 AT SEA STATION 1A AND SANSINENA SITE A9. NOTE A9 PEAKS AFTER DECEMBER 1976 INCIDENT

ABUNDANCE OF SOME COMMON PLANKTONIC ORGANISMS - STA A1



ABUNDANCE OF SOME COMMON PLANKTONIC ORGANISMS - STA A9



Text Table 1.

RELATIVE CONCENTRATION OF DOMINANT ZOOPLANKTON
(number/meter^3)

December 1, 1976	December 23, 1976	December 29-30, 1976
A2: 2532	UO1: 649	UO1: 227
A3: 903	UO2: 369	UO3: 605
A8: 1059	UO3: 331	UO5: 160
A9: 793		UO7: 379
		UO11: 708
		UO13: 453
		UO15: 700
		UO17: 557
		UO19: 709
		UO21: 389
		UO23: 400

The unusually high diversity may have resulted from the very high tides (7'+) during November and December, 1976, bringing into the harbor species that normally occur off-shore. The increased diversity was also found in samples taken Dec. 1 before the explosion outside the harbor, and at one station (A12) in the outer harbor.

The persistence of this high diversity in an area of an oil spill is unexpected since normally an oil spill of this magnitude would be expected to decrease diversity in an area by killing the more sensitive species and allowing only the hardy to survive. This, however, does not appear to be the case and it is possible that the spill did not have a toxic effect on the zooplankton. In support of this, Conover (1971) found that the two copepods, *Calanus finmarchicus* and *Temora longicornis* fed on weathered Bunker C oil particles and this was a major natural factor in the immobilization of the oil spill with no apparent toxic effects on the ingesting copepods.

There appears to be no other feature such as species collected or abundance encountered, which can be isolated to have been changed by the oil spill. For this reason the effect of the oil spill on the zooplankton assemblage appears to be minimal.

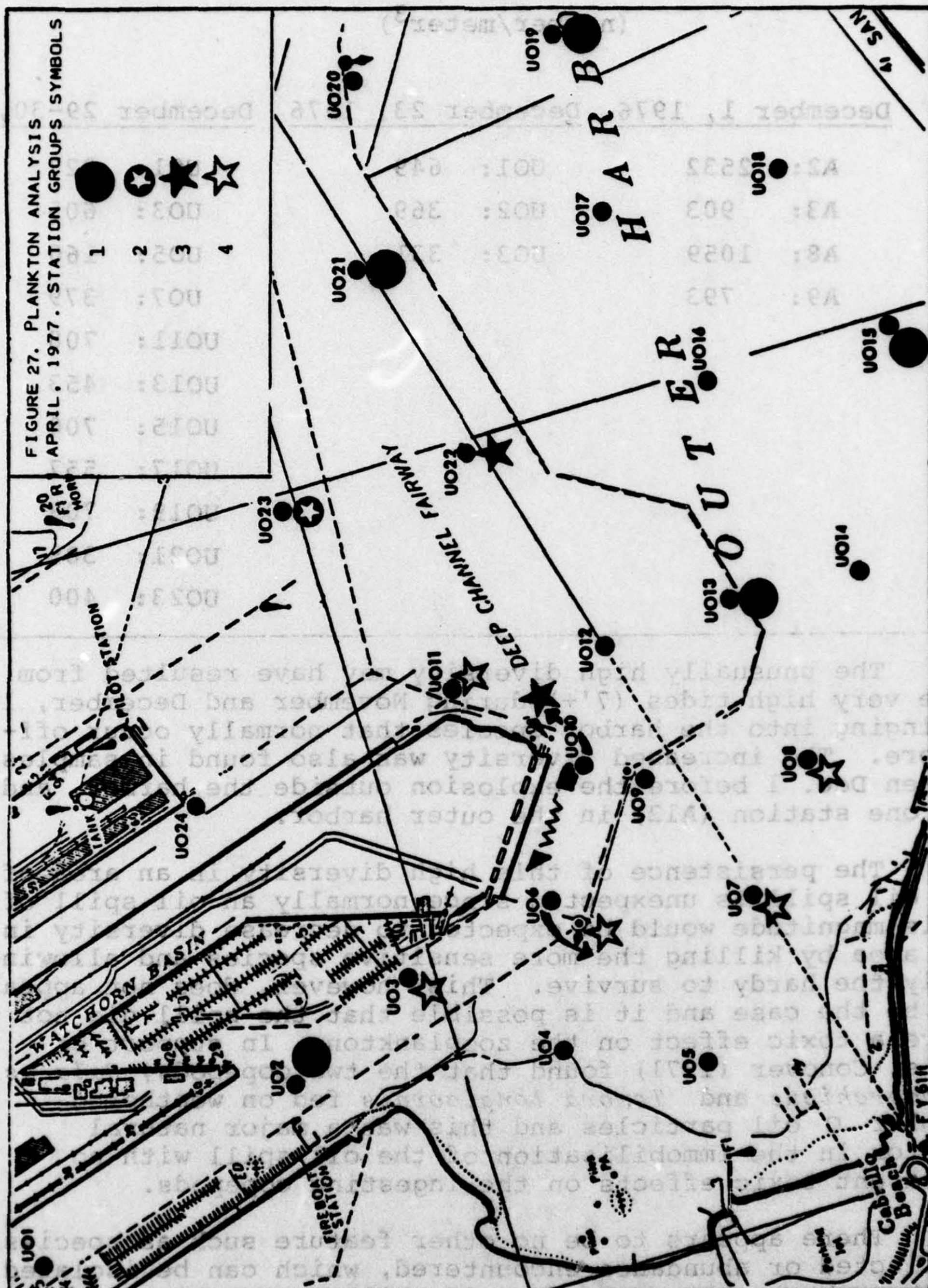


FIGURE 27. PLANKTON ANALYSIS
APRIL, 1977. STATION GROUPS SYMBOLS

** UNION OIL PLANKTON DATA * APRIL 1977 **

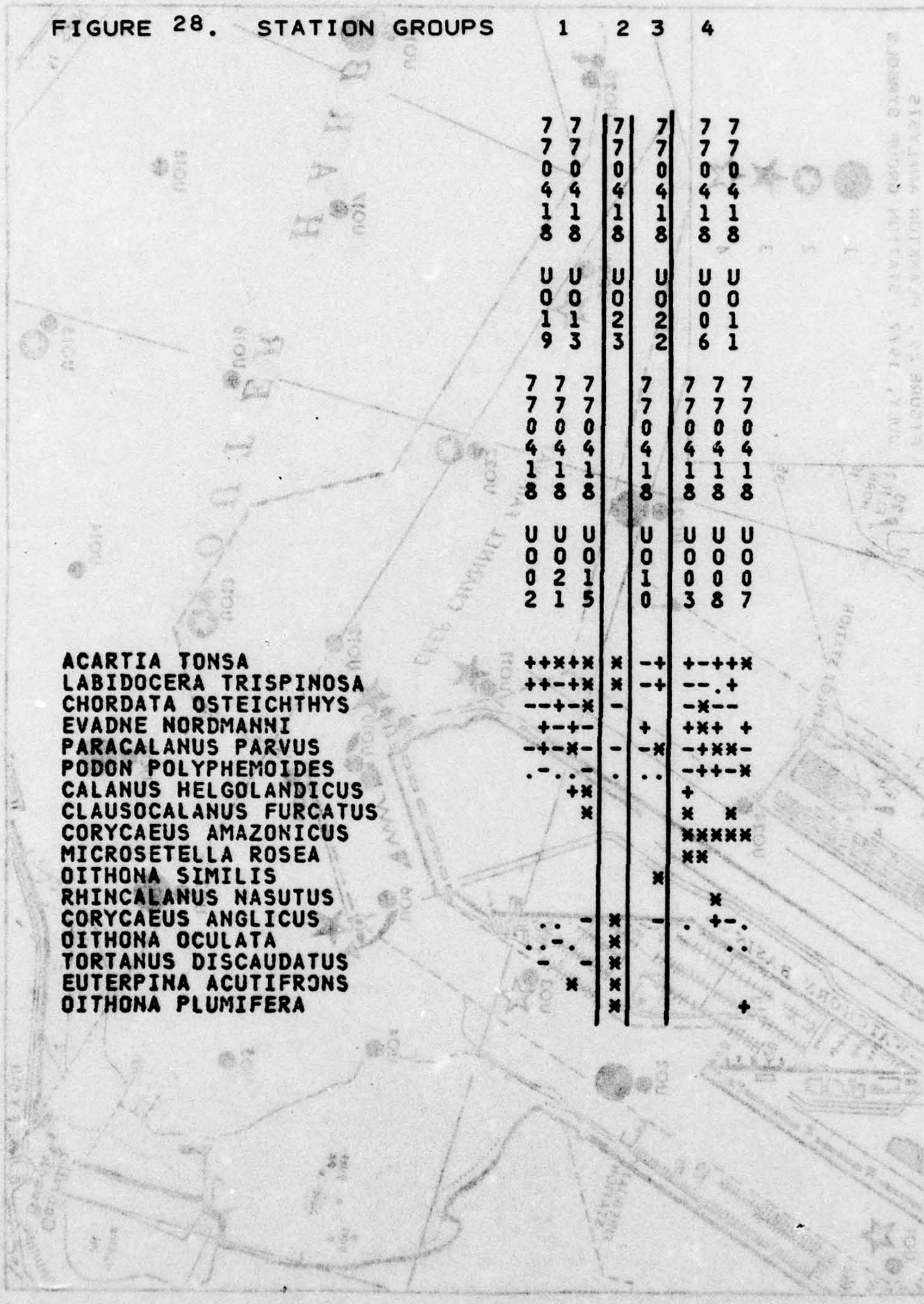


FIGURE 28. STATION GROUPS

	1					2	3		4				
	770418 U002	770418 U019	770418 U021	770418 U013	770418 U015	770418 U023	770418 U010	770418 U022	770418 U003	770418 U006	770418 U008	770418 U011	770418 U007
ACARTIA TONSA	+	+	*	+	*	*	-	+	+	-	+	+	*
LABIDOCERA TRISPINOSA	+	+	-	+	*	*	-	+	-	-	.	+	
CHORDATA OSTEICHTHYS	-	-	+	-	*	-			-	*	-	-	
EVADNE NORDMANNI		+	-	+	-		+		+	*	+		+
PARACALANUS PARVUS	-	+	-	*	-	-	-	*	-	+	*	*	-
PODON POLYPHEMOIDES	.	-	.	.	-	.	.	.	-	+	+	-	*
CALANUS HELGOLANDICUS				+	*				+				
CLAUSOCALANUS FURCATUS					*				*			*	
CORYCAEUS AMAZONICUS									*	*	*	*	*
MICROSETELLA ROSEA									*	*			
OITHONA SIMILIS								*					
RHINCALANUS NASUTUS											*		
CORYCAEUS ANGLICUS		.	.		-	*		-	.		+	-	.
OITHONA OCULATA	.	.	-	.		*						.	.
TORTANUS DISCAUDATUS		-			-	*							
EUTERPINA ACUTIFRONS				*		*							
OITHONA PLUMIFERA						*							+

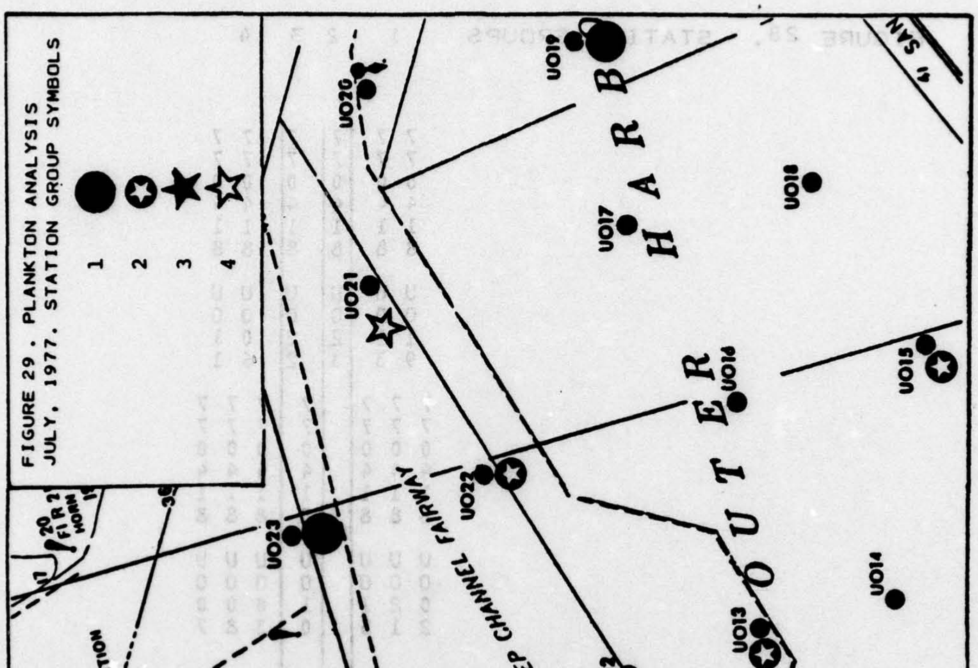


FIGURE 29. PLANKTON ANALYSIS
JULY, 1977. STATION GROUP SYMBOLS

** UNION OIL PLANKTON DATA * JULY 1977 ***

FIGURE 30. STATION GROUPS

STATION GROUPS	1					2			3			4		
	770718 U002	770718 U008	770718 U007	770718 U023	770718 U019	770718 U015	770718 U022	770718 U013	770718 U006	770718 U011	770718 U010	770718 U001	770718 U021	770718 U003
ACARTIA TONSA	+	.	*	*	+	.	.	.	+	+	*	+	*	*
PARACALANUS PARVUS	-	-	-	-	-	+	-	*	+	*	*	-	.	*
EVADNE NORDMANNI	.	-	-	+	*	-	-	-	-	-	+	.	-	.
PODON POLYPHEMOIDES	-	*	-	*	+	-	*	-	-	-	+	*	-	.
CORYCAEUS ANGLICUS	*	*	+	+	+	+	*	*					+	
OITHONA SIMILIS	*	*	*	*	+	-	-	-		+		-	-	+
CALOCALANUS STYLIREMIS	*	*			*									
CHORDATA OSTEICHTHYS				*				*						
ISCHNOCALANUS TENUIS								*						*
LABIDOCERA TRISPINOSA			+	+	*		*	+						
OITHONA PLUMIFERA				*	+									+
ACARTIA CLAUSI	-											*	-	-
OITHONA OCULATA					+	+	+	+			+	*	*	+
EUTERPINA ACUTIFRONS													*	

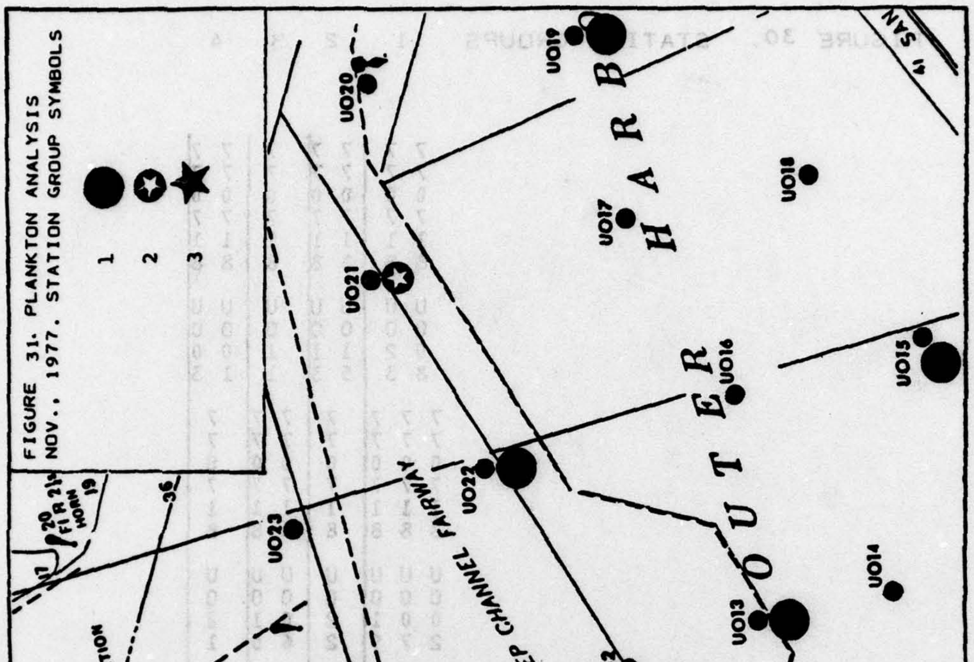


FIGURE 31. PLANKTON ANALYSIS
NOV., 1977. STATION GROUP SYMBOLS

** UNION OIL PLANKTON DATA * NOVEMBER 1977 **

FIGURE 32. STATION GROUPS 1 2 3

	1						2			3			
	771101 U007	771101 U008	771101 U015	771101 U019	771101 U013	771101 U022	771101 U011	771101 U021	771101 U010	771101 U001	771101 U002	771101 U003	771101 U006
EUTERPINA ACUTIFRONS			*									*	
OITHONA SIMILIS			*									*	
CORYCAEIDAE CORYCAEUS												*	
ACARTIA CLAUSI										+	+	*	*
ACARTIA TONSA	.	+	*	+	*	*	*	-	+	*	*	+	*
PARACALANUS PARVUS	-	*	+	*	+	*	-	*	+	.		-	+
PENILIA AVIROSTRIS	.	.	-	+	-	+	+	*	.	.	.	.	.
CORYCAEUS ANGLICUS	-	*	*	*	.	+	.	-	.				.
LABIDOCERA TRISPINOSA	-	+	*	-	+	+	-	.				-	-
EVADNE NORDMANNI	+	.	*	-	.	-	.	.	.			.	.
PODON POLYPHEMOIDES	*	+	*	-	-	-	.	.	-		-	+	-
CHORDATA OSTEICHTHYS							*	+	+				
OITHONA OCULATA			+				+	*	+	+			
PSEUDODIATOMUS EURYHALINUS							*						
CALANUS HELGOLANDICUS	+	+							*				
CALOCALANUS STYLIREMIS				*									
OITHONA SPINIROSTRIS				*			+	+					
CORYCAEUS AMAZONICUS						*							*
OITHONA PLUMIFERA						*							
EVADNE SPINIFERA					*	*							

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IMPACT OF THE EKOFISK BRAVO BLOWOUT (4/22/77)
IN THE NORTH SEA

Chairman: GERALD WADLEY
NALCO Environmental Sciences

THE FATE AND WEATHERING OF SURFACE OIL FROM THE BRAVO BLOWOUT

Tore Audunson
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The paper presents a description of the drift spreading, dissipation and weathering of the oil on the surface following the Bravo blowout. Simulations of the drift, spread and dissipation of the oil on the surface is compared to field data. The dissipation computations are based upon a simple one parameter budget model. Tidal currents are included in the drift (spreading) computations. The results of the computations show fair agreement with the observations. Drift card releases and statistical computations are also presented which illustrate the fortunate timing of the spill with regard to coastal pollution.

1. INTRODUCTION

We may properly start a discussion on oil-spill at sea by simply stating that "the ocean is motion". This is certainly an obvious statement, but a statement which should be kept in mind by all of us who deal with problems in all branches of oceanography. Whether we are interested in the movement of sand on a beach, the design of a ship, biological aspects or the spreading of oil on the sea a proper understanding requires first an understanding of the physical phenomena of the sea.

The motion of the sea is basically the result of the interaction of two thin films that cover our planet: the atmosphere and the ocean. So closely linked are the two major fluids that it is difficult to separate meteorology from physical oceanography in dealing with problems of oceanic movement.

The above statements are of particular significance when it comes to drift and spreading of oil spilt at sea. In the early phases of an oil spill most of the oil will be on the sea surface where it under the influence of wind and current will be carried along different trajectories. Depending upon many factors the oil will gradually be mixed into the underlying water masses.

Investigations of the behaviour of oil on water have been carried out since late 1920 (Stroop 1927). More intense studies of the fate of oil on water followed the grounding of the tanker "Torrey Canyon" in 1967. The development of offshore oil production and transportation facilities has been accompanied by a growing concern for the possibility of oil spills and the associated potential for adverse impacts upon coastlines and oilinfected waters. This has lead to a growing research into various phenomena governing the behaviour of oil on the water. Our present understanding of such processes are, however, still rather limited. This is true for instance for: Wind, wave and current induced drift and spreading; natural dispersion as a function of oil and ambient conditions; chemical and biological degradation of oil; plus back ground knowledge of ambitient conditions (oceanographic, meteorological) at possible sites for oil spills in various regions , for example in the North Sea and along the Norwegian coast.

In this respect through scientific studies of potentially pollution-hazardous real oil spills may serve as valuable sources of information and increased understanding.

In the following will be presented some observations of the drift spreading and weathering of oil from the Bravo blowout in the North Sea.

2. THE BRAVO OIL SPILL

The Bravo blowout started the night to Saturday April 22. 1977. This blowout is the first major blowout to occur from a production well in the North Sea.

The Bravo platform is situated at $56^{o}34'$ N, $3^{o}12'$ E, Figure 1. The shortest distance from the platform to the shore (Norwegian coast) is approximately 280 km.

According to information from Phillips Petroleum the maximum production capasity of well B-14 (Bravo) is 2.830 tons oil and 1.410 tons gas per day. Observations indicate that approximately 35 to 40 % of the oil evaporated prior to and shortly after the oil hit the water surface. Thus we may estimate that approximately 1.700 tons/day of stabilized oil reached the water surface , whereas the amount of gas released at the platform was about 2.500 tons/day. The estimated amounts are probably somewhat too high because the flow through the production pipes may have been partly restricted by mud or other foreign articles.

The well was capped around 12 o'clock on April 30th or approximately seven and a half days after the blowout started. During this period the gushing jet of oil was intensly mixed with large amounts of sea water. The sea water was sprayed into the oil jet and over the platform at a rate of approximately 2.000 tons/hr.

3. OCEANOGRAPHIC CONDITIONS AT THE SPILL SITE

3.1. General remarks

The North Sea is surrounded on three sides by Great Britain, France, Belgium, Netherlands, Germany, Denmark, Sweden and Norway. The surface area of the North Sea is about 575.000 km^2. The greatest depth is found along the Norwegian trough with a maximum of about 700 m in the Skagerrak. The North Sea platou is by and large around 100 m deep with the greatest depth to the north and shallower waters to the south. Around Ekofisk the depth is around 70 m.

The oceanographic conditions in the North Sea show considerable variations both temporally and spatially.

The current conditions in central portions of the North Sea where the major portion of the Norwegian offshore activity takes place, are unstable and dominated by tidal currents and by wind driven currents. Residual currents are weak. More pronounced semipermanent currents are found along the various bordering coast lines; southward outside Scotland and probably also England, northward outside Netherlands, Germany, Denmark, Sweden and Norway. Outside the Norwegian coast the current velocity may reach large values. Velocities above 1 m/s are commonly found.

The tidal velocities likewise exhibit fairly large geographical variations in both amplitude and main direction. In the central portions of the North Sea we find that the tidal velocities vary between 10 cm/s and 40 cm/s.

Stratified waters are mostly found north of 54° N. Such stratification is particularly strong along the Norwegian coast where the brackish water of the coastal current flows on top of the heavier Atlantic water masses.

In the central portions of the North Sea we find that the average surface temperature goes towards a minimum value in March (5°C) and a maximum value (15°C) in September.

The meteorological conditions are also characterized by lack of stability. Sudden changes in the weather-conditions are frequently found. During the winter season the winds in the North Sea are mainly from south-west whereas the winds during the summer season are mainly from north-west. Mean wind strength during summer is 3 - 5 m/s and during the winter 8 - 14 m/s.

The wave climate in the North Sea is certainly also of importance in connection with oil spills and possible pollution hazards. Analysis of more than twenty-five years of data from wind and sea state (Håland and Småland 1977) indicates that a significant wave height between 4 and 9 meters may be expected 16 % of the time whereas waves between 0 and 1.2 m may be expected 34 % of the time.

3.2. Some Oceanographic Observations During The Blowout Period

Hydrographical conditions during and after the blowout period were observed by several investigators. Observations were made using both CTD sondes and standard Nansen casts. In figure 2 is shown the vertical distribution of temperature salinity and density along the line A-B in figure 3. The data were taken on May 1, 1977. The horizontal distribution of temperature at five meter depth in the vicinity of the platform is shown in figure 3. (Ljøen 1977).

As it appears the water masses were nearly homogenious vertically. The sea surface temperature was approximately 1.5°C below the mean value for this time of the year. The core feature shown in figure 2 and 3 includes the possibility of a vortex circulation in the area.

Current measurements were carried out with selfrecording current meters in position indicated in figure 3. Data was only obtained from three of the indicated stations. Measurements were made close to the bottom and near the surface. A progressive vector diagram from the station closest to the platform (1) is shown in figure 4. The combined effect of a drift current (probably wind included) and tidal currents is clearly demonstrated by these results.

During the observational period the current velocities reached values up towards 50 cm/s approximately 8 m below the surface whereas the velocities near the bottom reached values up to 30 cm/s. Mean values where 20 cm/s and 10 cm/s respectively. The measurements did indicate significant velocity gradients with depth (Audunson et al. 1977).

During the blowout period waves were measured both with a wave rider buoy and by observations from the weather ship "FAMITA" located to the north of the Bravo platform.

Wave measurements carried out with a wave rider buoy May 2. under sea and weather conditions reported unsuited for operation of oil boom equipment, showed a significant wave height of approximately 2.6 m. The Norwegian Meteorological Institute reports that wave measurements from the weather ship "FAMITA" gave similar results for May 2. They also report that wave conditions during the blowout period and the first half of May were fairly calm with significant wave heights equal to or less than 2 meters most of the time.

In the periode April 22. to June 15. the wind direction was changing evenly between northerly and southerly. The wind force did reach waves up to 23 m/s, but most of the time, however, the wind force was below 10 m/s.

4. THE FATE OF THE OIL ON SEA

4.1. Physical Appearance Of Oil On The Surface

The appearance of the oil on the surface may be described through a number of stages: (i) Near the platform the oil spread into a nearly

triangular brownish film with a thickness of about 1 mm. The width of this slick was about 100-200 m and its maximum extent about 1 km. (varying as a function of wind and waves). (ii) At the outer edge of this film there developed a thicker (1 - 20 mm) and yellowish brown water in oil emulsion. This water in oil emulsion was quite unstable and with a maximum water content of approximately 70 %. (iii) The emulsified slick was further divided into long (1-2 km) narrow stripes of emulsified oil with thicknesses (1 - 20 mm). Somewhat erroneously this stage was referred to as "the slick". This "slick", however, was not a single slick. It consisted of several of the long stripes mentioned above. The width of these stripes were 10 meters or less. The distance between the stripes was less than 10 meters near the platform. In central portions of the slick this distance was observed to be between 100-1.000 m. The finer structure of the stripes was again smaller stripes. Towards the end of the blowout period and after the well was capped more stable water in oil emulsions were formed. These emulsions had a brownish appearance . (iv) The edges of the emulsion stripes were continously broken up into smaller oil lumps. The size of the lumps were from 2 - 20 mm in diameter during the blowout. With increasing time they gradually disintegrated into much smaller oil modules (1 - 3 mm in diameter). The stable water content in the oil lumps was about 50 to 60 %. (v) Large areas around the emulsion stripes were covered with a very thin film of oil ("Blue shine") with an estimated thickness of about 0.01 - 0.001 mm. During periods of strong winds this film was broken up and it formed long narrow stripes similar to the emulsion stripes. The "blue shine" was appearantly quite susceptible to dispersion into the underlying water masses

4.2. Loss Of Light Fractions (Evaporation, Dissolution)

Oil samples were collected from a number of stations both during the blowout and in the period following the capping of the well. (Audunson et al. 1977). The oil samples were kept in cold storage until analyzed in the laboratory. The samples were analyzed in a gas chromatograph and flame ionization detector. One month old Ekofisk crude oil was used as a reference for stabilized crude.

As mentioned previously 35 to 40 % of the oil evaporated before or shortly after the oil hit the sea surface. The evaporation and dissolution of lighter fractions continued after the oil came on the sea surface. After twelve hours it was found that the amount evaporated was ca. 50 %. After 15 days the total loss of lighter components amounted to 68 % of the oil fraction initially spilled from the well. The high temperature (75°C) and droplet formation of the oil fraction sprayed into the air were probably major factors leading to the rapid initial evaporation.

In figure 5 is shown the rate of evaporation as function of time after the oil hit the surface. The per cent evaporated refers to the amount of oil which hit the surface. In the same figure is also shown evaporation curves for Ekofisk crude obtained in laboratory experiments at two temperature levels. The agreement between the laboratory experiments corresponding to the 6°C curve and the field observations from the Bravo accident is good. We may recall that the sea surface temperature was approximately 6°C during the blowout period .

4.3. Density And Viscosity Changes

The density of oil samples was measured using a pycknometer. The viscosity of the oil samples was determined with a Brookfield synchro-lectric Viscometer, spindle no. 7.

The density of the oil was found to increase (from a theoretical value for pure crude of 0.85 to 0.87 kg/dm^3) to 0.95 kg/dm^3 after two days on the sea surface. The mixing of salt water into the oil is assumed to be a first order effect for the density increase.

As already mentioned the stable water in oil emulsion was found to be almost 56 %. The average diameter of the water droplets in the oil after some time was found to be approximately 10^{-6} m.

Significantly larger changes with time was found for the viscosity of the oil on the sea. The viscosity increased from an initial value of approximately 7.500 cp (at 6°C) to a value close to 70.000 cp (6°C) after two days at sea. The reason for this large increase we assume to be a continued effect of weathering and evaporation pluss the emulsification of the oil. The latter effect is , for a 70 % water in oil emulsion, shown (Audunson et al. 1978) to result in an order of magnitude increase in viscosity as compared to pure Ekofisk crude. In the above referance it is shown for instance, that for Ekofisk crude with 31 % evaporation loss, the viscosity (6°C) for pure Ekofisk crude is 1.650 cp and close to 15.000 cp for Ekofisk crude emulsified to 76 % water content.

Some characteristics of the collected oil samples are shown below.

Date	Position	Per cent evaporated of total disch.	Spesific Weight	Viscosity cp (6°C)	Water content %
25/4	56.33N,3.14E	40	0.926	7.400	75
30/4	56.39N,3.28E	49	0.928	7.600	70
2/5	56.40N,3.00E	57	0.943	67.000	52

Table 1. Some characteristics of collected oil samples.

4.4. Drift And Dispersion

The drift of the oil was mainly followed by Phillips Petroleum and by the Action Control Centre in Stavanger. There were good agreement between the two data sets. The observations were made from air planes, from helicopters and from boats. The observations were mostly visual only and the appearance of the oil was described as blue shine or as thick oil. Estimates were also given with respect to the per centages coverage of the sea surface with oil.

In figure 6 is shown some examples of the observations of oil on the surface. From the start of the blowout and up to April 28.,

the oil drifted mainly in an eastward direction. After April 28. the main portion of the slick gradually turned towards north and at the end of the blowout period it also turned slightly towards north-west.

During the blowout period the blue shine area reached a maximum value of 3.000 km^2 whereas the extent of the thick oil reached a maximum of 500 km^2. The growth of the blue shine area and the thick oil area is depicted in figure 7.

It is interesting to note that this separation of two distinct phases of the crude oil on the sea into a thin film domain and an area of thick emulsified oil was characteristic reported by Jefferey (1972) and by Cormack et al. (1977) in their experimental oil releases at sea.

We should also note that the observed tendency of the major portion of the drifting oil to rapidly emulsify and to divide into separate strips and lumps renders the more simplistic surface tension spreading laws inapplicable. It seems more appropriate to consider the effect of ocean turbulence when evaluating the possible horizontal extent of a crude oil infected area. Within this area one may perhaps more properly try to express the number density of oil particles.

The characteristic horizontal extent of various oil slicks reported in the litterature have in figure 8 been plotted on a diagram for the growth with time of the spatial variance of oceanic horzontal turbulence (Audunson 1975). As it appears from the figure the observed "rate of growth" of the maximum extent of oilspills falls well within the expected values considering turbulence induced effectes.

Computations and observations of the continued drift of the oil after May 3. and towards the middle of June show that the main portion of the oil first drifted northward from Ekofisk about 120 km (to 58°N, 3→4°E).Around May 12 there was a shift in the weather conditions and the remaining portion of the oil drifted southward and back towards Ekofisk. Around June 13 both computations and observations showed that the remaining oil was about 120 km south of Ekofisk (55°30'N, 3-4°E). (See figure 9. The Marine Institute in Bergen then reported that they found the remains of Bravo oil within an area of approximately 55.000 km^2 but with the highest consentrations within an area of roughly 400 km^2 (Heyerdahl 1977). Computations imply that the remaining oil after this date continued to drift in a south-southeasterly direction (See figure 9. In part this is corroborated by the recovery of driftcards released during the blowout. As will be shown later most of these were found on the northern coast of Netherland.

The amount of oil on the surface at any time is a function of many factors. Waves and surface turbulence are main factors leading to the natural dispersion of oil into the water column. Other factors will certainly be present as shown in figure 10.

When a freely drifting oil slick is subjected to wave action it may be shown that the oil layer may become thickend and thinned at the crest and trough respectively (Leibovich 1975). If the wave breaks, oil particles are intensly mixed down into the water. If the buoyant rising

velocity of the oil particles exceeds the downward vertical turbulent transport velocity, the particles subsequently floats back to the surface.

The mechanical action of the waves on the oil is considered to be of major importance for the breaking up of the emulgated oil stripes into oil lumps.

The mechanism for further division of the lumps into smaller particles are probably also dependent upon wave or turbulent energy in the water. Pressure effects from the repeated submergene to various depth of the buoyant lumps may also be important. In figure 11 is shown how oil lumps taken from the Bravo oil spill behaved in quiescent and stirred beakers with salt water. As may be seen the lumps in the agitated beaker after some days disintegrated into several small particles. The other "lump" remained unchanged. This phenomenon must be of great significance for the rate of natural dispersion of oil from the surface. The ability of the turbulent water masses to keep the oil in suspension is certainly a function of particle size.

The rate at which natural dispersion takes place will also vary with the type of oil.

During the Bravo blowout natural dispersion was of importance for the "lucky" outcome of this incident. No oil from the spill has to our knowledge, been reported on any shore.

A simple expression for the amount of oil on the surface may be written as follows

$$\frac{dQ}{dt} + \lambda_n Q = q(1-f(t)) \qquad (1)$$

where $\lambda_n Q$ is the term describing the loss of oil from the surface by natural dispersion (and other processes) $q(1-f(t))$ describes the loss by evaporation, $Q,_t$ represents the change with time t of the amount of oil Q on the surface whereas q is the spill rate of oil per unit of time.

Estimates of the amount of oil on the surface during the blowout periode and in the first days following the blowout have been carried out using the available slick observations. These estimates were used to establish a value of λ, the natural dispersion parameter. The parameter has the unit day^{-1} and may thus be regarded as a characteristic time or half-life for the oil on sea.

Used on the data from the Bravo blowout we found that $\lambda = 0{,}1$ day^{-1} gave a fair agreement between the solution of the above equation and the estimates of the number of tons of oil on the surface as a function of time. This λ-value corresponds to a halflife for the oil on the surface of about 7 days.

In figur 12 is plotted the estimated observed amount of oil on the surface as a function of time. On the same figure we have included the solution to equation (1) for $\lambda = 0.1$ and 0.15 day^{-1}. From the same figure we may also see the losses due to evaporation alone and thus infer the dispersion loss.

The value of λ_n estimated from the Bravo-data corresponds to the mean wind conditions during the period in question (8.5 m/s). Other wind forces will, however, change the dispension rate, i.e., increasing with stronger winds and decreasing with winds of lesser force.

It seems reasonable to assume that the dispersion rate will be related to the vertical transport of momentum in the upper water masses. This transport of oil particles may phenomenologically be compared to the vertical transport of suspended material. Reynolds analogy is often used in connection with the transport of suspended material (Yalin 1972). A consequence of this assumption is that there is a constant ratio between the vertical transport of momentum and suspended particles. The following relationsiip has been assumed from surface shear considerations.

$$\lambda_n = \lambda_o \left(\frac{U}{U_o}\right)^2 \tag{2}$$

where U_o (=8.5 m/s) is the wind force at which λ_o has been estimated and U is the windforce of interest.

Using the above it was found that 45 days after the blowout was stopped (i.e. June 15.) there should be

1) 60 tons of oil on the surface for λ_n equal to a constant ($\lambda_n = \lambda_o$)
2) 120 tons of oil on the surface for variable λ_n computed according to equation (2).

The variable λ_n computations does have a better agreement to the observed value of 115 tons of Bravo oil on the surface which was carried out on June 7. to 16. (Heyerdahl 1977).

4.5. Drift Card And Drift Bouy Results

During the period April 6. to April 28. approximately 2.000 10 cm x 15 cm plastic wrapped drift cards were released from the nearby Charlie platform.

During and after the blowout three satelite positioned drifting buoys were set out directly in or near major oil slicks. The buoys were equipped with transmitters for the NIMBUS-6/RAMS satelite system. The release of these buoys was done in cooperation with the Norwegian Meteorological Institute and Christian Michelsens Institute.

The trajectory of one of the buoys is shown in figure 13 together with positions of the main portion of the spilled oil. The result from the experiment indicated that the use of such buoys for tracking of oil spill represents a very promising technique. Great care should, however, be taken in the design of the buoys both in order to obtain the desired drift characteristics and to assure identical drift factors for all buoys beeing used.

The results from the release of drift cards before and during the blowout illustrates how a small shift in the blowout date could have resulted in a much greater risk for shore pollution.

In figure 14 is shown the places of recovery for the drift cards released one and two weeks prior to the blowout and the drift cards released during the blowout. The first recoveries of cards released prior to the blowout was from cards at the Danish coast after 36 days, whereas the first recoveries of drift cards released during the blowout was reported from the German coast about 100 days after the release. The blowout thus seemed to occur during a period with long drift times to the shore. Computations of drifts trajectories using available wind and current information gave similar results.

5. MODELING OF THE DRIFT AND SPREADING OF THE OIL

5.1. Computations Of Drift And Spreading During And After The Blowout

Simulations of the drift and spread of the oil on the surface has been carried out using a deterministic model (OILSIM). The model requires as input, wind and current data. At present the model covers the geographical area shown in figure 15. A more detailed description of this model is given by Krogh (1977) and Audunson et al. (1977).

For drift computations are also needed information about the evaporation rate for the oil, the dispersion constant mentioned earlier, the spill rate, the wind drift factor, the "coriolis deflection", grid size and geographical location. The model may accomodate both residual currents and tidal currents.

From drift card experiments and from the results of computations using data from the Bravo blowout, we have found that a wind drift factor of 2.5 - 3 % and a coriolis deflection of 12-15^{o} gave results in good agreement with observations.

It was also found that the inclusion of tidal currents was necessary for simuting the oil spill near the platform where the "width" of the area with thick oil slicks was less than the tidal excursions (5 km, see figure 4).

In figure 16 are shown some example results from the drift calculations. Both the extent of the "thick oil" area and the total oil infected area (referred to as the "blue shine area") are given in the figure. As it appears there is a fair degree of agreement between observations and computations.

The computed drift of the oil after May 4. has already been given in figure 9. The three different trajectories in that figure represent the trajectories of three fairly large slicks with heavy emulgated oil observed north of Ekofisk on the given date.

5.2. Results of Long Term Oil Spill Simulations

In connection with an impact evaluation of possible consequences of oil spills from the Ekofisk area, there has been carried out both statistical and deterministic computations of the fate of oil from assumed spill incidents. For the statistical simulations we have used a modified version of a program originally developed by Dietzel et al. (1976). Five years of wind data from the Norwegian Meteorological Institute was employed for these statistical computations. In addition we have performed deterministic computations for assumed single oil spill incidents of six months duration.

In figure 17 is given an example of the results from the statistical computations. The spill rate is assumed to be from 2.000 - 14.000 tons/day, the spill duration from 5 - 15 days if bridging occurs, and 80 - 180 days if a relief well has to be drilled. The bridging probability is set to 20%. Natural dispersion and evaporation effects are included.

From these results we may observe that Denmark may expect the highest average number of tons (or per cent spilled oil) on shore followed by the west and southwest coast of Norway. There is, according to these results approximately 60% probability that the amount of oil on shore will be less than or equal to the given average amounts. We may further note that the chances for no oil at all on shore are around 7% for Denmark and around 13% for Norway.

The fact that no oil from the Bravo blowout has been reported on any shore must, therefore, be considered very fortuitous indeed. Major factors were according to these results the short duration of the spill, the particular weather and oceanographic conditions during the spill and the effective natural evaporation and dispersion of the oil on sea.

In figure 18 is shown an example of the results from the deterministic computation. The blowout is assumed to start on January 9. 1975 and last for 6 months. The results illustrate the distribution of oil impact upon the North Sea area and along the various coast for the particular period chosen. The various contour lines enclose areas with an equal number of "hits" from drifting oil daylots. The number of such "hits" is given in the figure. For the chosen six month period about 1.5% of the spilled oil reached shore. The computations further indicate that for a 2.000 tons/day blowout the average hydrocarbon consentration in the upper five meters may roughly be expected to be of the order 100 – 200 ppb assuming that the dispersed oil may be regarded as a conservative tracer.

The shortest drifting time ashore was found to be around 9 days. The lowest amount of oil on shore was in these computations for the April/May period, i.e. for the time of the year of the Bravo blowout. These results also again demonstrate the importance of the rapid capping of the well. The oil infected area in the North Sea during the Bravo blowout was quite small compared to the extent indicated by the present computations of a long term blowout.

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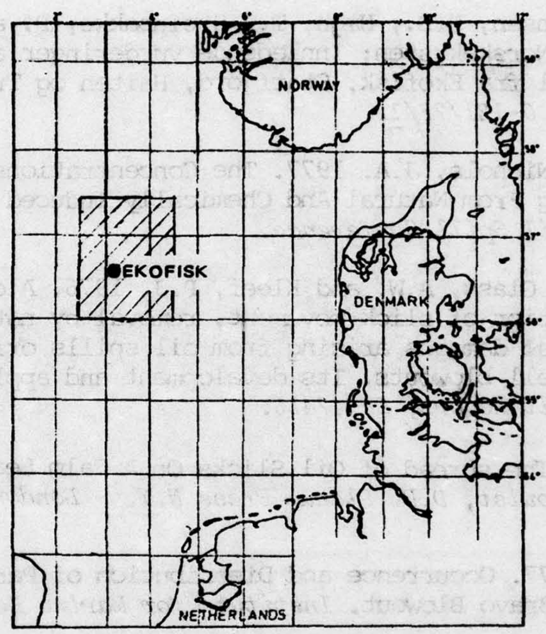

FIG.1 The North Sea and the Ekofisk site

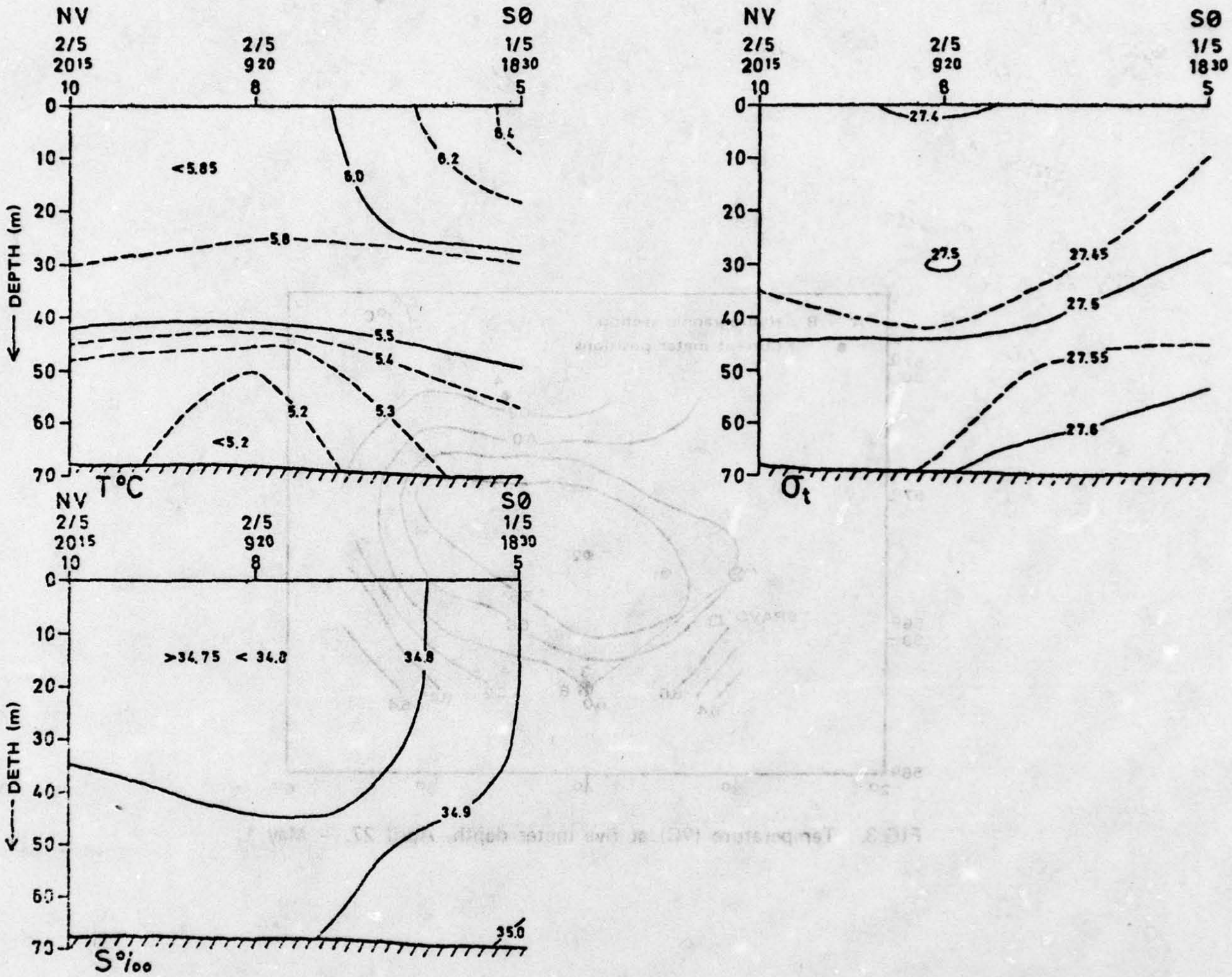

FIG.2 Isolines for the vertical distribution of salinity (S^0/oo), temperature (T^0C) and density (σ_t)=(ρ−1000)kg/m^3)

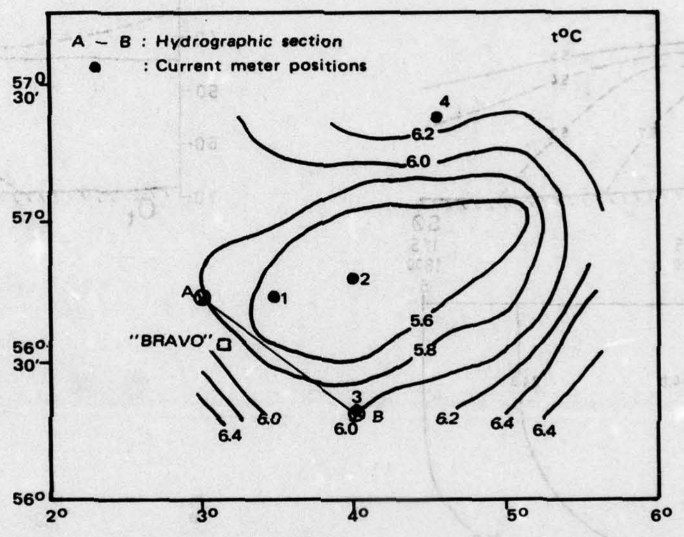

FIG.3. Temperature (°C) at five meter depth, April 27. – May 1.

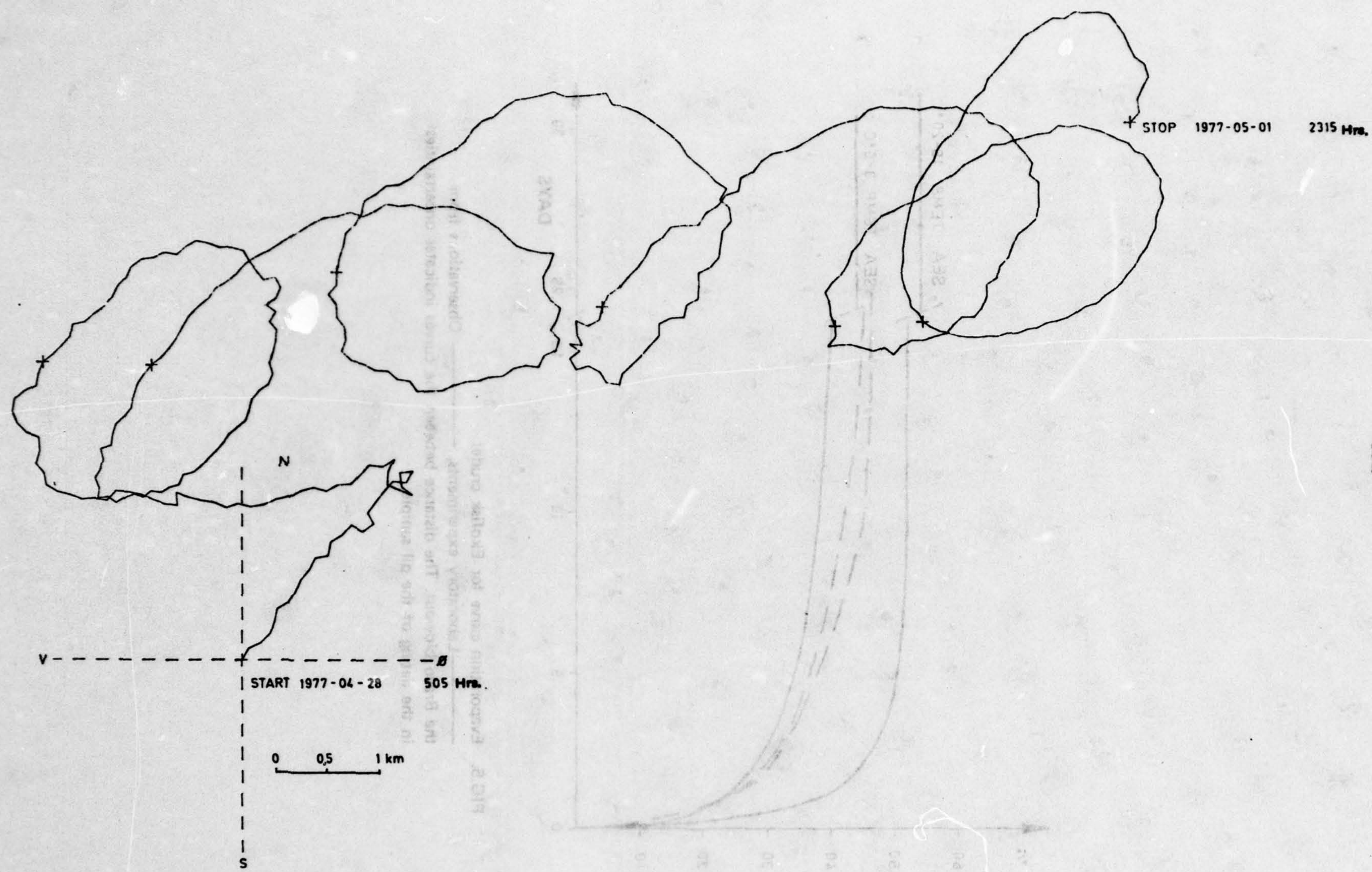

FIG. 4. Progressive Vector diagram for the current at 8m depth at station 1

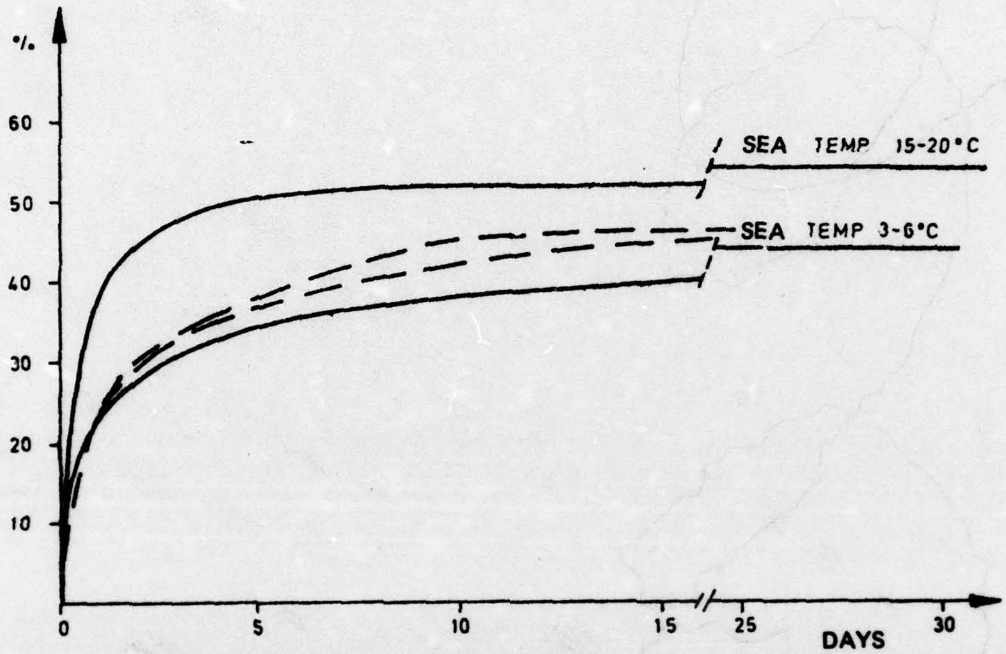

FIG.5. Evaporation curve for Ekofisk crude:
———— Laboratory experiments, - - - - - - - - Observations from the Bravo blowout. The distance between the curves indicates uncertainties in the dating of the oil sample.

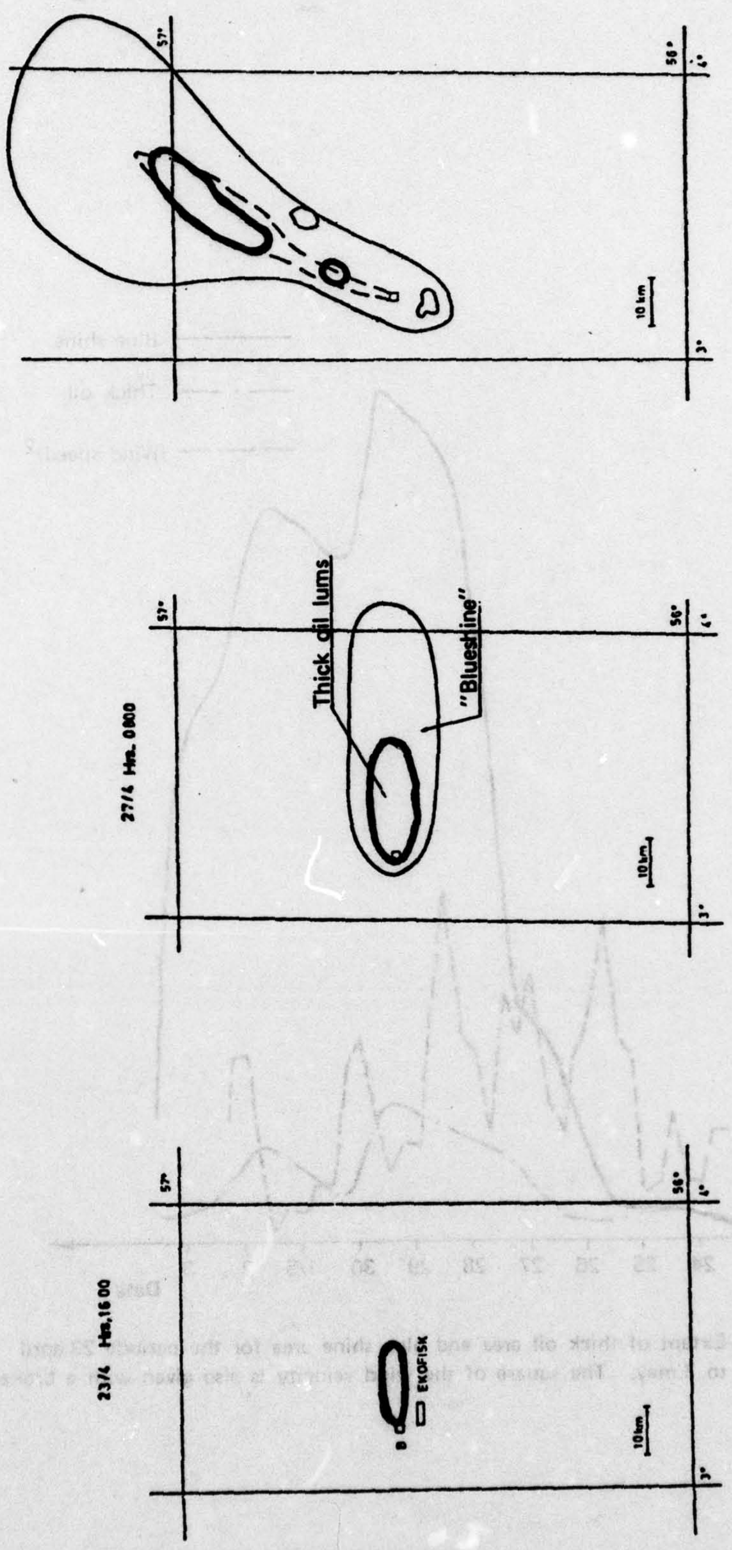

FIG. 6 Examples of the observations of oil on the sea

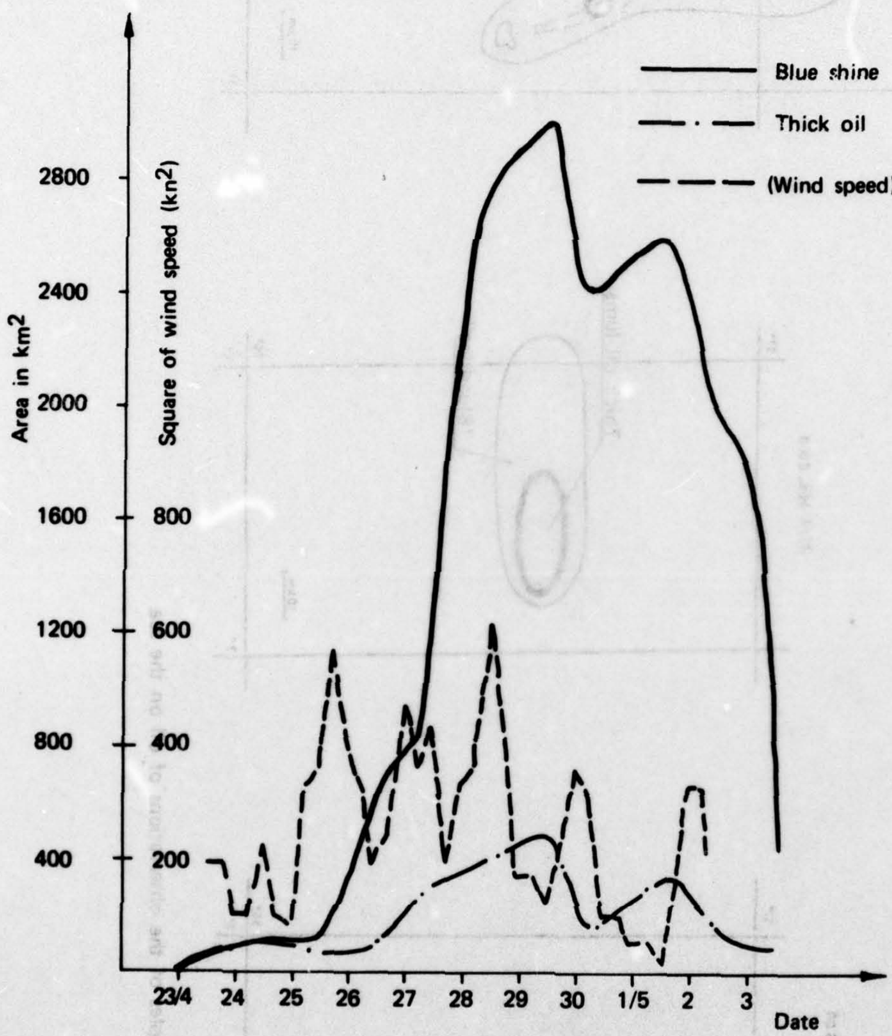

FIG. 7 Extent of thick oil area and blue shine area for the periode 23.april to 3.may. The square of the wind velocity is also given with a broken line.

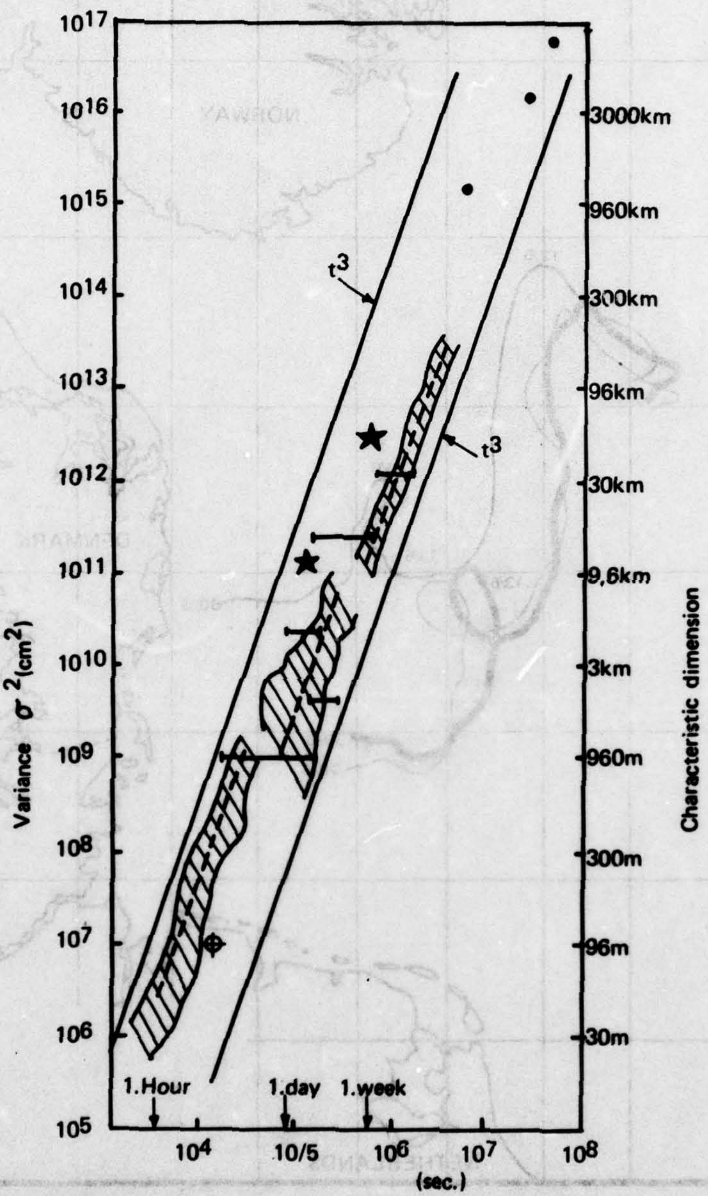

FIG. 8. Variance vs. diffusion time fit of the t^3 low locally (OKUBO, 1974). The horizontal solid lines represent observed characteristic dimensions of oil. spills (FAY, 1969). Filled stars represent the blue shine area from the Bravo blowout

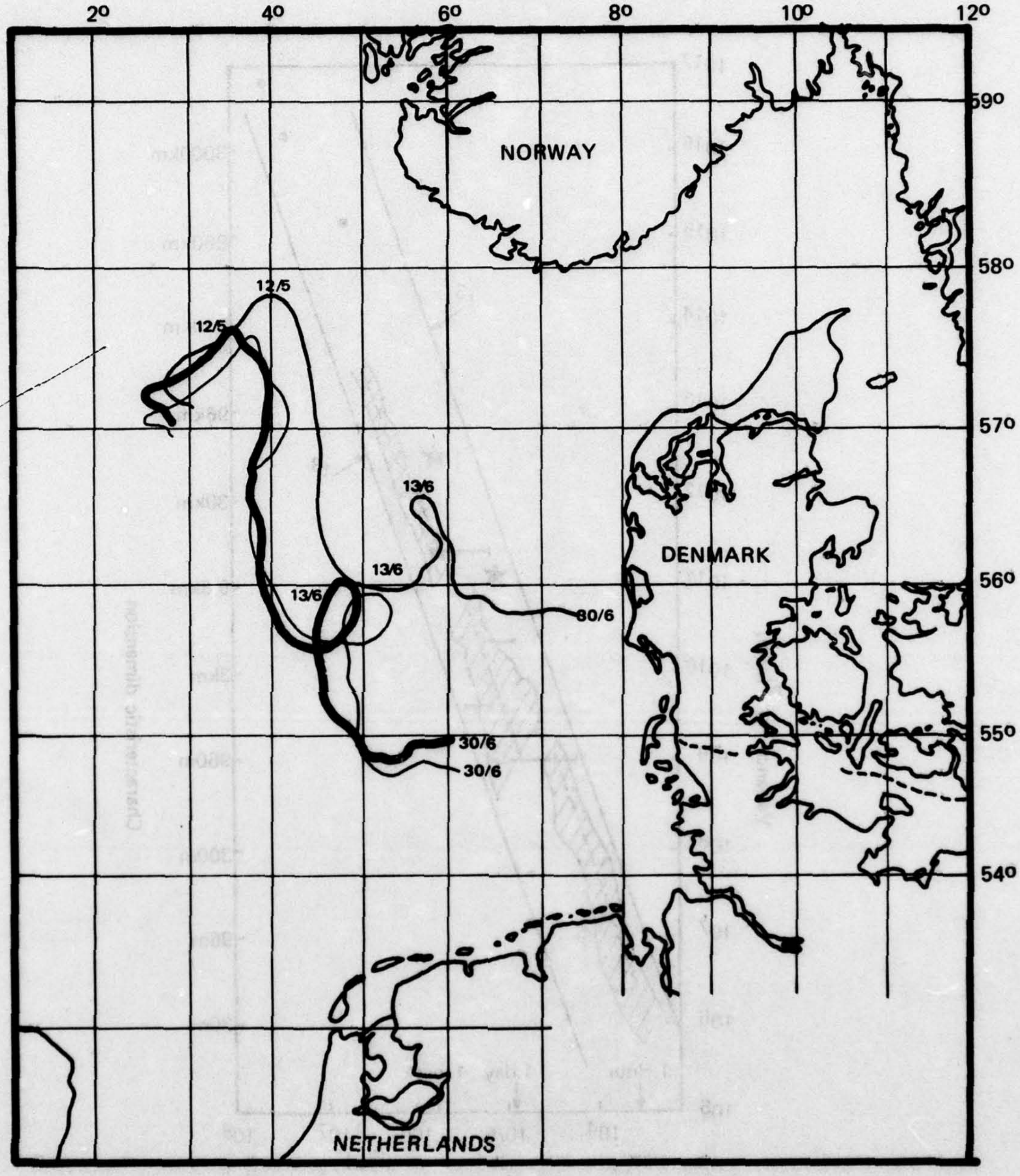

FIG. 9 Computations of trajectories for spilled oil after May 4. Observations of Bravo oil was made around May 12. and June 13.

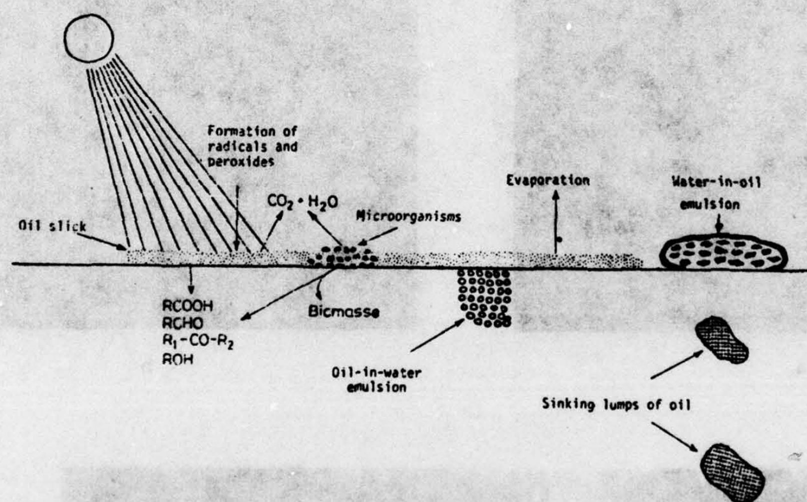

FIG.10 Weathering and dispersion effects of oil on the sea

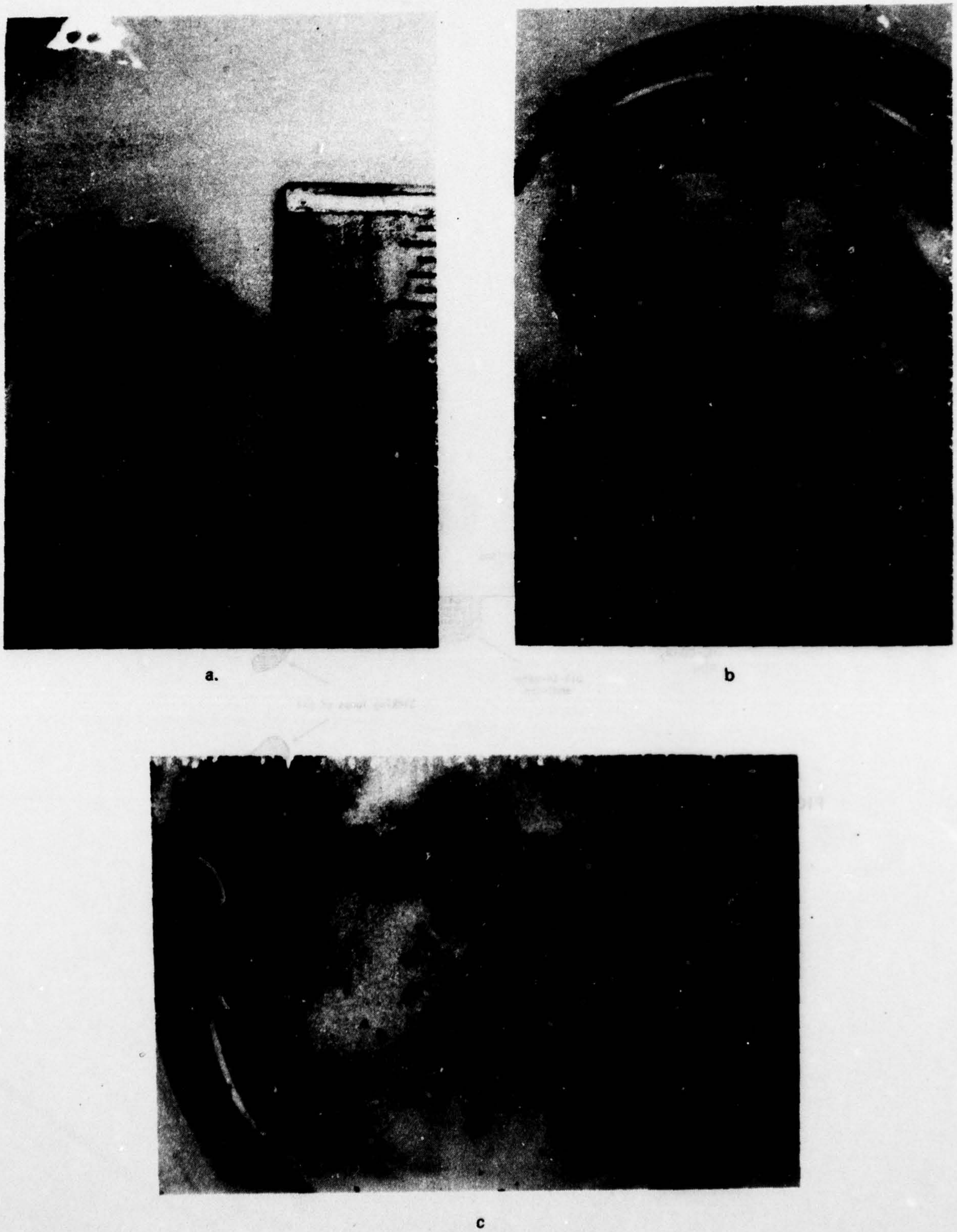

FIG.11. a) Typical oil lumps observed five days after the blowout stopped.
b) Similar lump of oil after 7 days in a beaker with quiescent water.
c) Same as b., but with a rotating stirrer in the beaker.

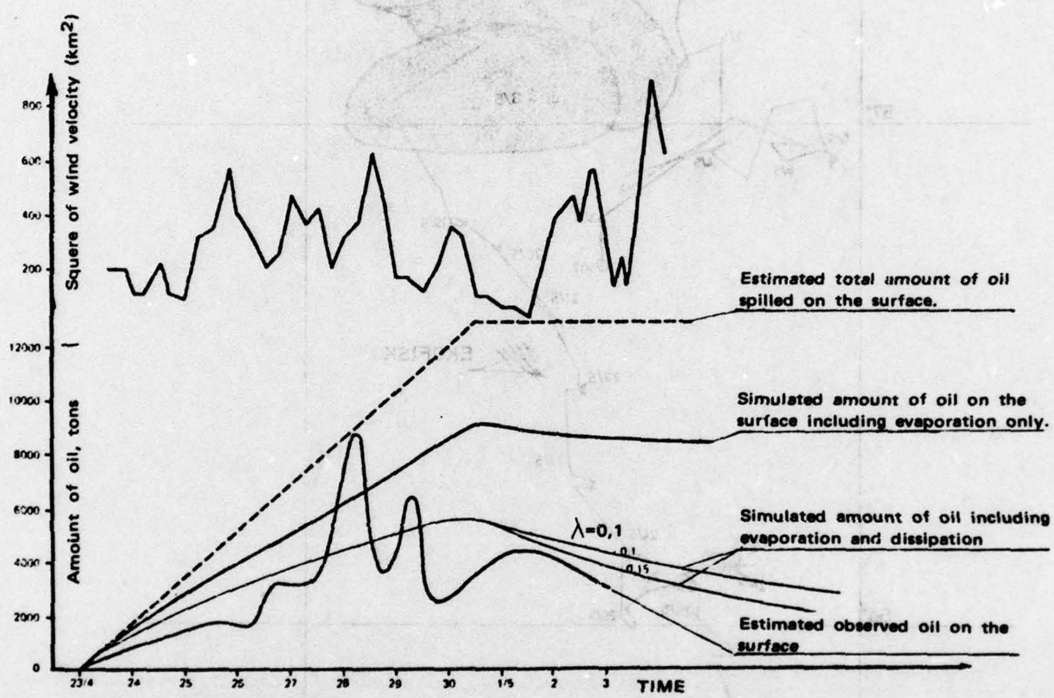

FIG.12. Variation with time of the amount of oil (tons) on the surface

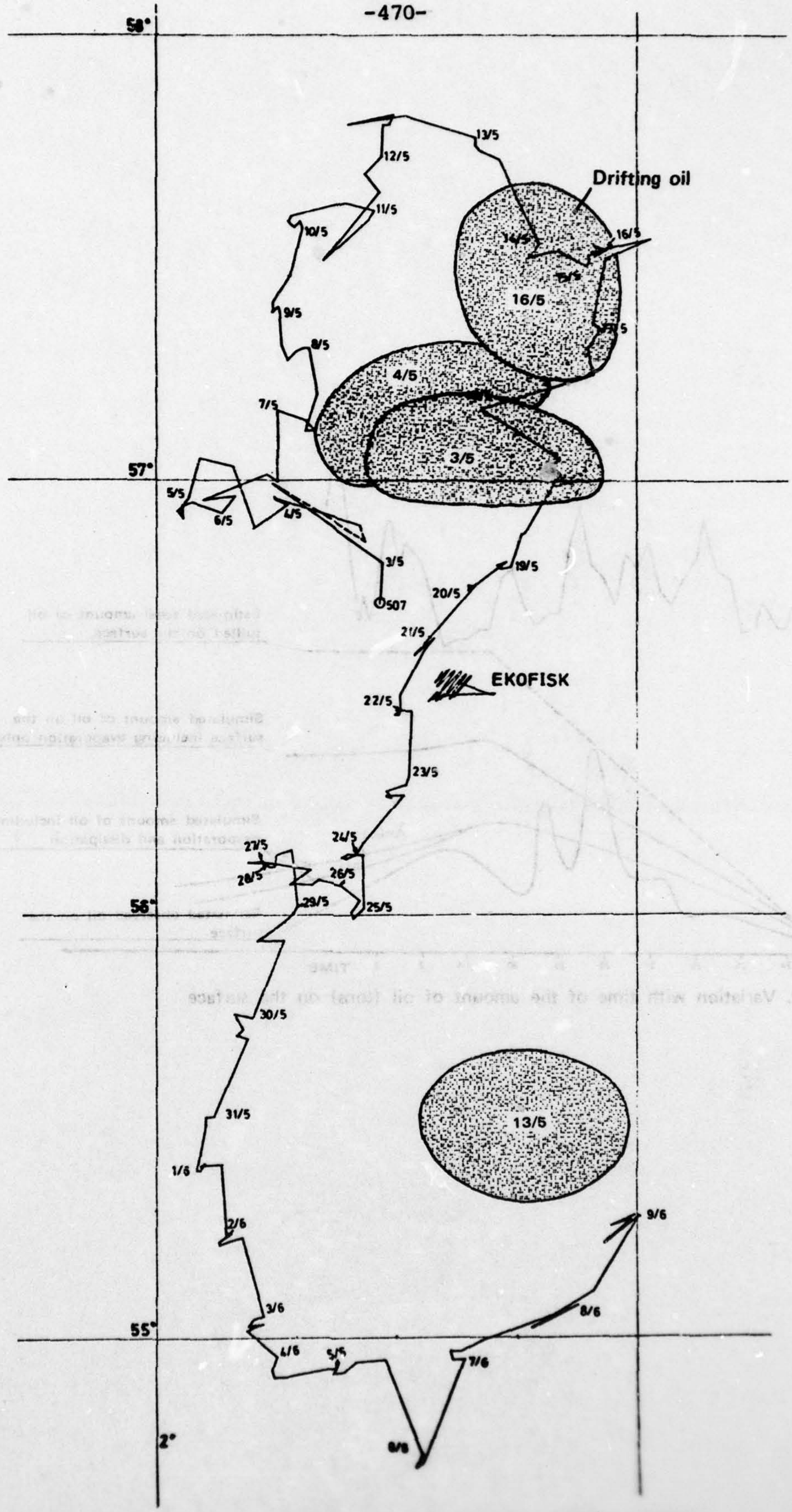

FIG.13 Trajectory for drifting buoy. Cross hatched areas indicate positions of the drifting oil spill.

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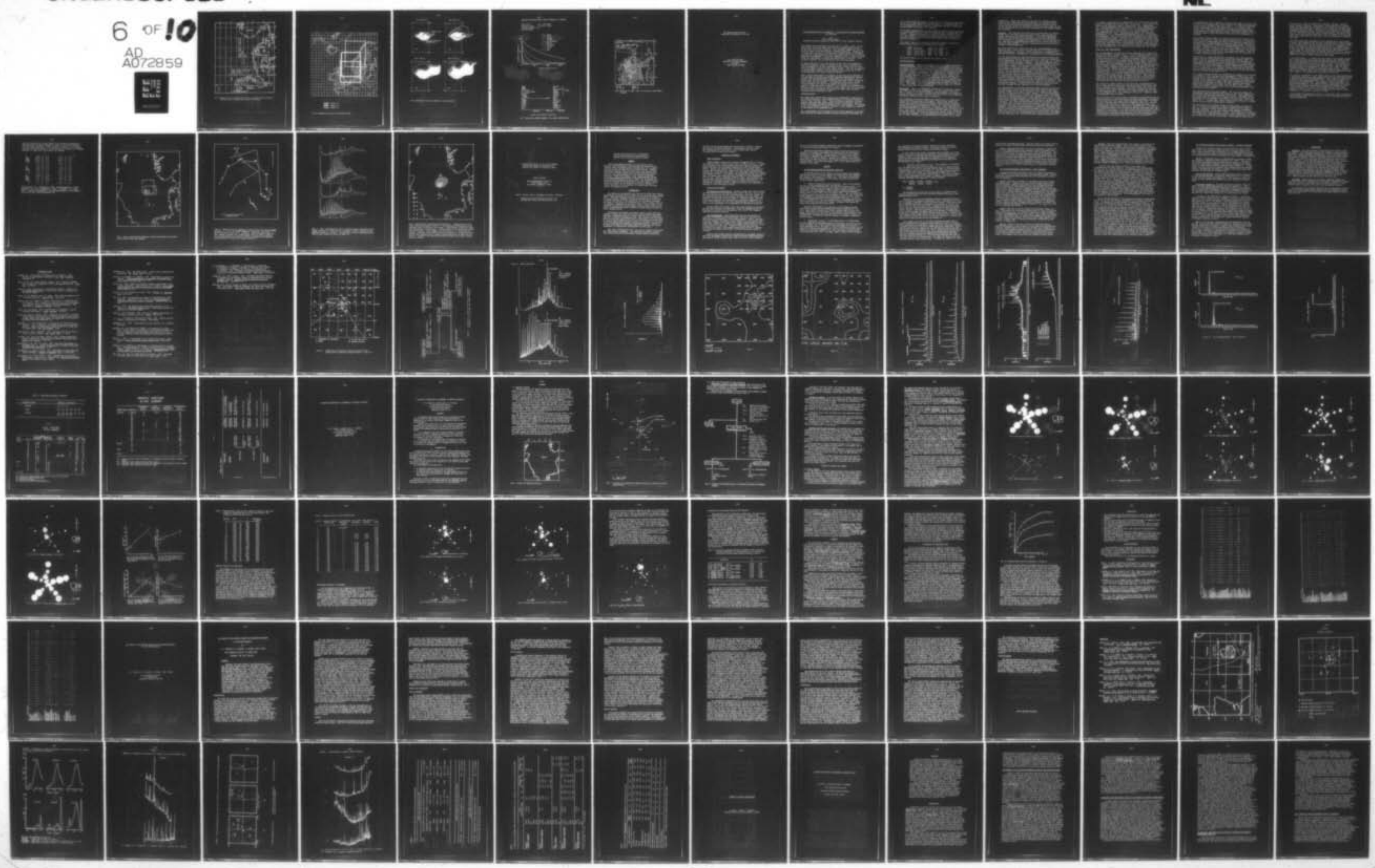
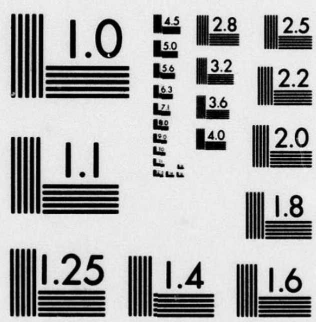




MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

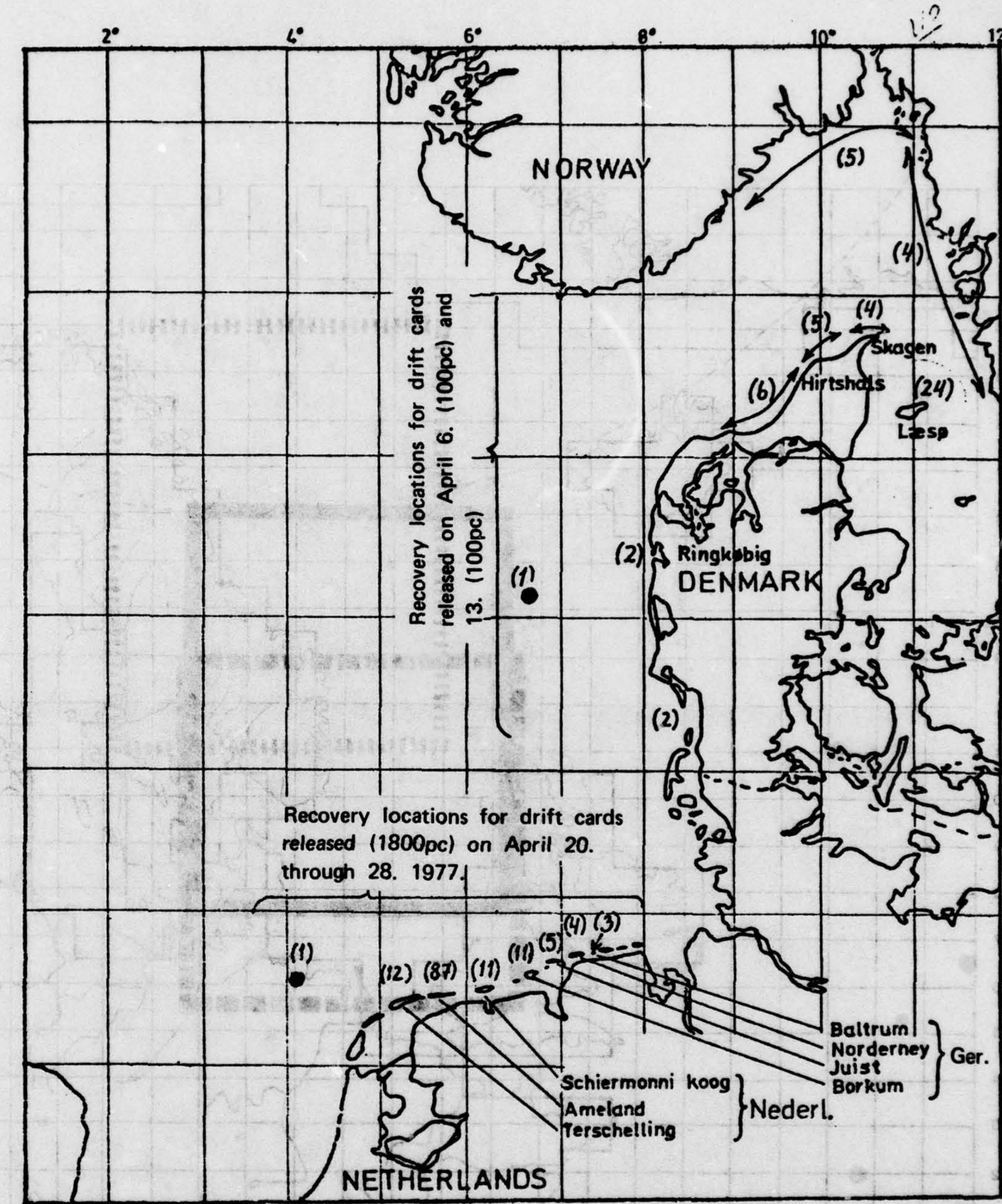


Fig. 14. Recovery of drift cards released from Ekofisk in the periode of April 6. to April 28. 1977. The number in brackets refers to number of cards found.

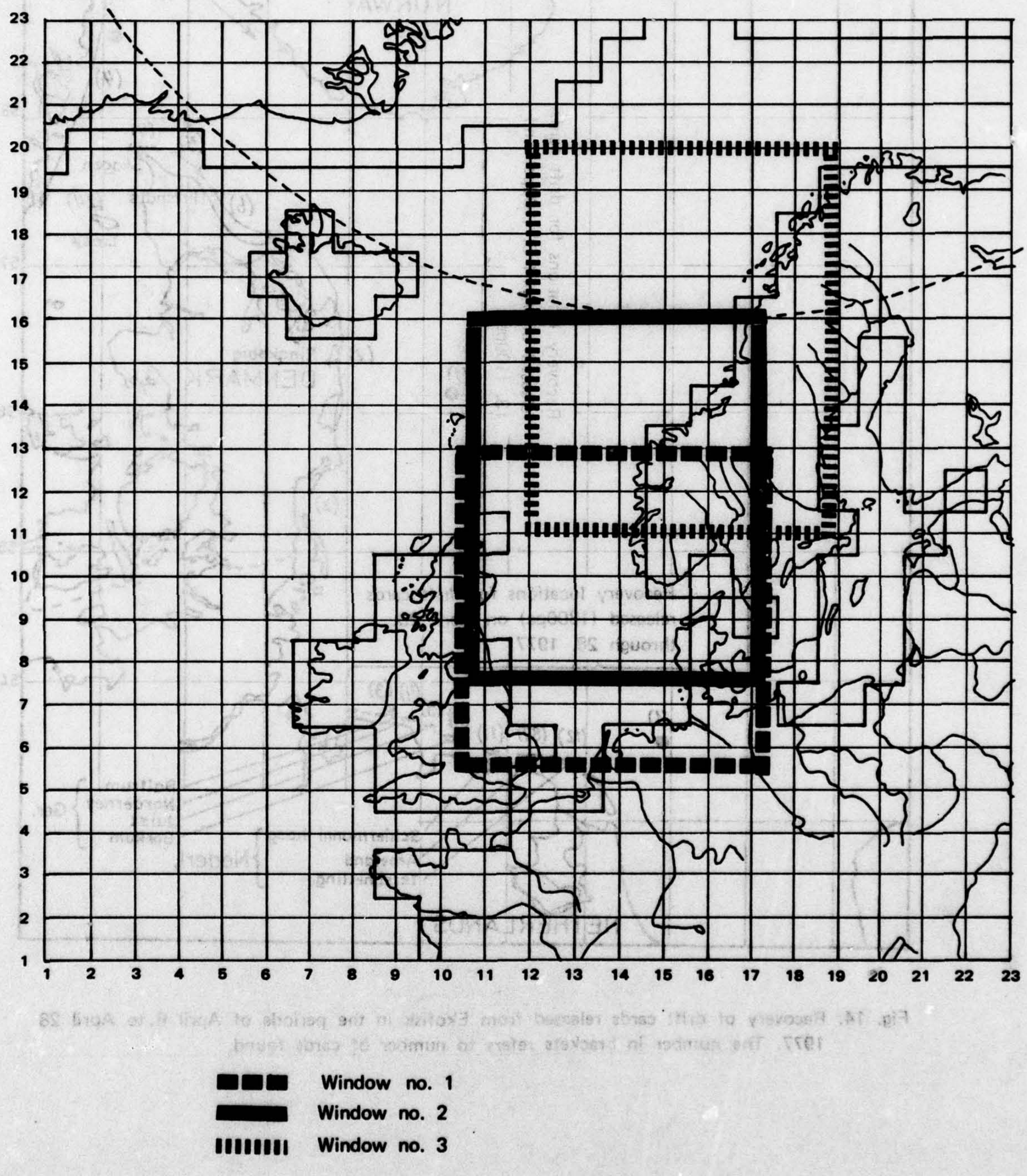


Fig. 15. Geographical area covered by the deterministic model.

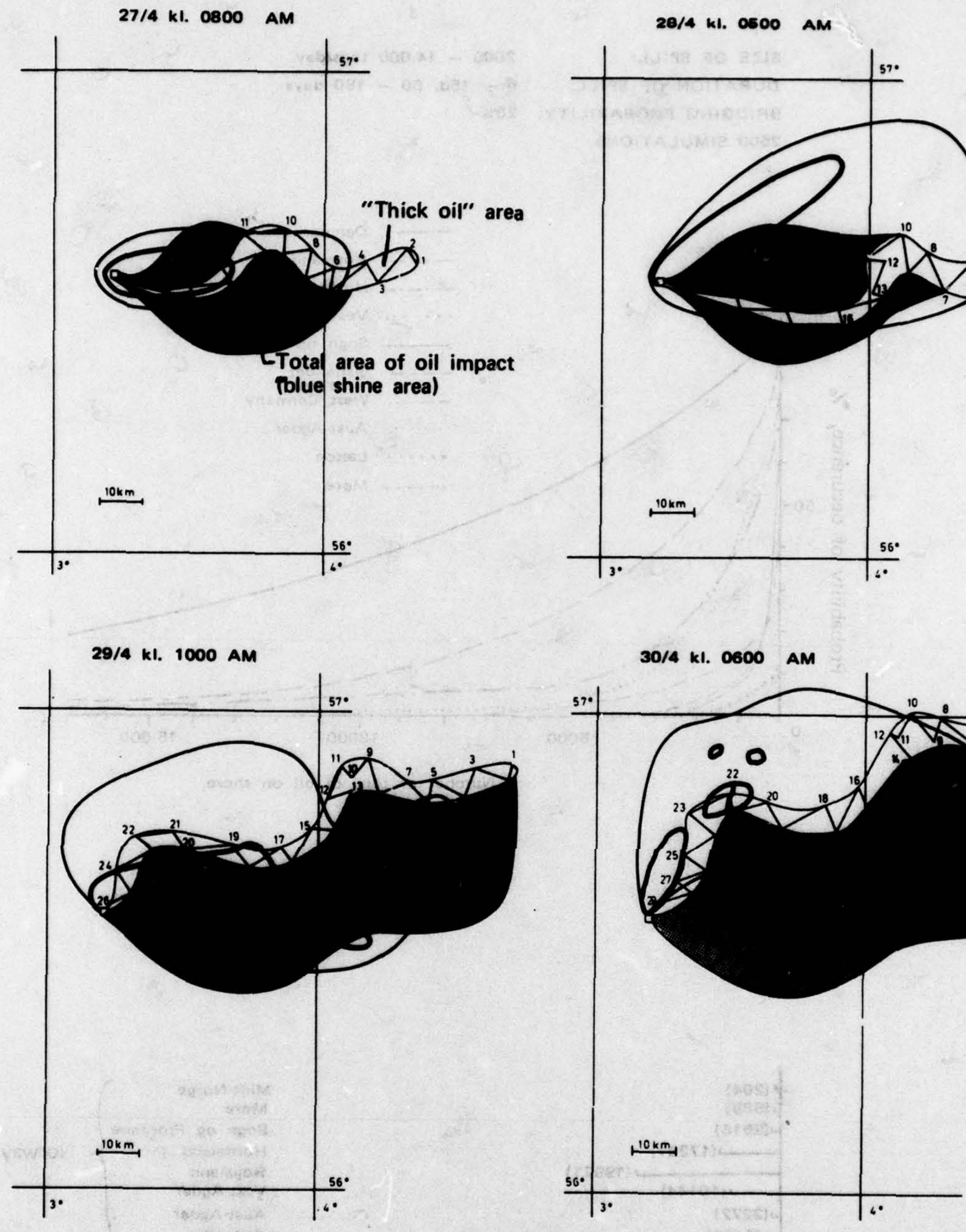
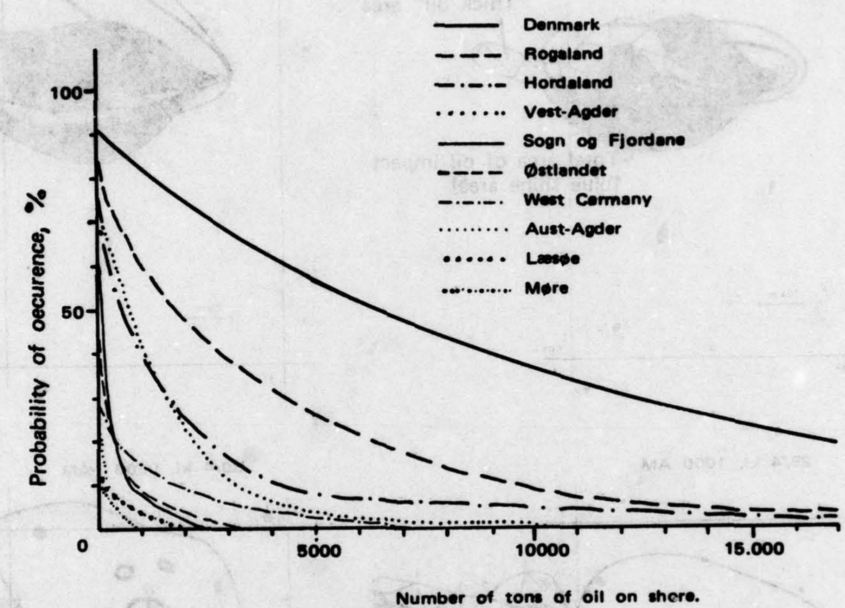


Fig. 16. Simulations of the drift and spread of oil near the platform.

COASTAL POLLUTION IMPACT FROM A BLOWOUT AT "EKOFISK"

SIZE OF SPILL: 2000 – 14.000 tons/day
DURATION OF SPILL: 5 – 15d. 80 – 180 days
BRIDGING PROBABILITY: 20%
2500 SIMULATIONS



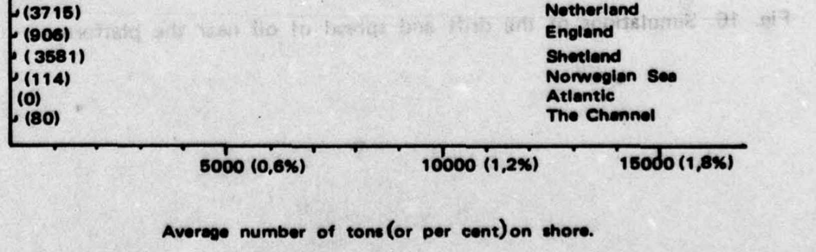


Fig. 17. Results from statistical computations for an assumed Ekofisk Blowout.

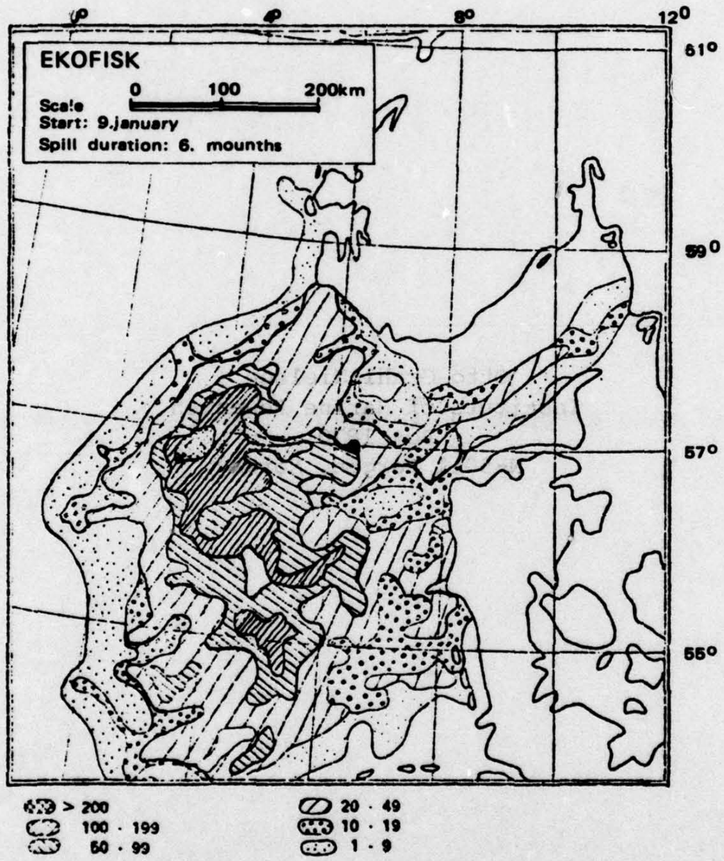


Fig. 18. Distribution of "impact - areas" for an assumed six month blowout at Ekofisk.

THE EKOFISK BRAVO BLOWOUT: PETROLEUM HYDROCARBONS IN THE SEA

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THE EKOFISK BRAVO BLOWOUT. PETROLEUM HYDROCARBONS IN THE SEA

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The Ekofisk Bravo Blowout occurred the 22 of April, 1977. During seven and a half days before the well was capped approximately 20 000 tons of oil were released. The blowout resulted in a heavy research effort from the Institute of Marine Research. Commencing 36 hours after the start of the blowout standard chemical, biological and physical oceanographic surveys were performed as well as special pollution investigations. One of the objectives was to study the spreading and distribution of petroleum hydrocarbons in the sea. The chemical analyses were performed by gas chromaotgraphy.

In areas with fresh oil on the surface in the near surroundings of the Bravo platform, within 10 nautical miles, up to an excess of 300 micrograms of oil were detected per liter water with no gradient in the upper 5 meters of the water column. The oil was present as oil-in-water emulsion and the analysis was carried out by gas chromatography with flame ionisation detection.

With a mass spectrometer as detector on the gas chromatograph it was possible to identify and quantify alkylated naphthalenes, phenanthrenes and debenzothiophenes originating from the blowout over a larger area, at least 60 nautical miles away from Bravo, during the first weeks after the blowout. The detection limit was 0.05 µg/l, and no gradient was found in the upper 10 meters of the water column. Using the same aromatics it was possible to distinguish tar balls of Bravo oil from tar balls of other origin, and also to exclude the Bravo oil as the source of pollution in some water samples collected south of Ekofisk in June.

INTRODUCTION

The North Sea contains fish resources of considerable importance to the coastal countries. International fisheries in this area amount to about 3 mill. tons per year. These resources reproduce on rather specific spawning sites spread over the entire North Sea, some of which are located around the Ekofisk field. This applies, for example, to the very important mackerel resource, where Ekofisk is centered in the middle of its spawning area.

As a consequence of the blowout from the Bravo platform in the Ekofisk field the Norwegian Institute of Marine Research undertook the

task of describing the exposed living resources and the possible effects of the oil on their physiology and behaviour. An important part of the investigations was to study the distribution and fate of petroleum hydrocarbons in the marine environment.

A scientific program was carried through on several cruises covering the period from 36 hours after the outbreak until 2 months after its closure. Based on information on the distribution and drift of the oil, grid systems of stations were planned for each cruise to cover both the polluted waters as well as the neighbouring non-polluted waters for reference.

This paper reports the results of chemical analyses of petroleum hydrocarbons sampled on the following 5 cruises:

KNM	"Sleipner"	April 24	- April 25
R/V	"G. O. Sars"	April 27	- May 1
R/V	"Johan Hjort"	April 27	- May 4
R/V	"G. O. Sars"	May 10	- May 16
R/V	"Johan Hjort"	May 31	- June 17

The areas covered by the vessels are shown in Fig. 1.

EXPERIMENTAL

Water Sampling. Water was sampled with 2.8 l bottles mounted in a frame with lead weights at the bottom and suspended from a buy. The bottle was stoppered when lowered and the stopper was removed by pulling a string. Great care was taken to avoid visible oil on the surface. As the main emphasis was placed on the horizontal distribution of petroleum hydrocarbons, samples from 1 m depth were taken at most stations. At certain selected stations samples were also collected from 5 and 10 m to investigate the vertical distribution. In these cases a half inch hose was used for support of the water sampler with the string for release of the stopper inside the hose. This rather primitive sampling method worked well down to 10 m. The bottles were retrieved open, and the upper 50 - 100 ml of water were immediately discarded.

Extraction. During the "Sleipner" and the two "G. O. Sars" cruises the water was extracted immediately. To the samples from the other cruises 30 ml column-distilled dichloromethane were added to prevent biological activity, and they were then stored in the dark for subsequent extraction upon return to Bergen.

For extraction, the water sample was poured into a 3 l separatory funnel with teflon stopcock and stopper. The sample bottle was rinsed very carefully with 50 ml dichloromethane which thereafter was transferred to the separatory funnel. The extraction was performed by thorough hand shaking for 1 minute. After separation of the dichloromethane the extraction was repeated twice with 25 ml each time. Both times the dichloromethane was first used for rinsing of the sample bottle. After these rinsings the sample bottle was ready for the next sampling. The combined extracts comprised 60 - 70 ml due to slight solubility of dichloromethane in seawater and to some

evaporation. They were stored in the dark for analysis onshore. Controls were taken daily by going thorough the procedure three times with 25 ml dichloromethane as described, but without seawater. In this manner control of contamination during the extraction and analytical procedures as well as of the cleanliness of the sample bottles was obtained.

Analysis. The extracts were dried with approximately 5 g sodium sulfate which had been freed from hydrocarbon contamination by soxhlet extraction with dichloromethane. Thereafter appropriate aliquots of the extracts were concentrated on a rotary aspirator. The evaporation was stopped when approximately 0.5 ml solvent was left, and this was quantitatively transferred to a small vial with a sonically shaped bottom. Further concentrating was achieved with a stream of dry nitrogen gas.

The final analysis was performed with gas chromaotgraphy in two different ways: with a flame ionisation detector for determination of total hydrocarbons, and with a mass spectrometer as detector for selected aromatics: naphthalenes, phenanthrenes and dibenzothiophenes.

For the determination of total hydrocarbons the extract aliquot was concentrated as described above to about 10 µl which were quantitatively transferred, by two rinsings with 15 µl each time, to a capsule of a Perkin-Elmer automatic sampler. The chromatography was performed in a Perkin-Elmer 900 gas chromatograph with a SP 2100 packed glass column, with nitrogen, 20 ml/min., being used as carrier gas. After each sample a blank of pure solvent was run under identical conditions and the recorded signal was used as base line for the preceeding chromatogram. The areas of the chromatograms over the base line and between the peaks representing the C_{14} and C_{22} normal alkanes were determined by planimetry and converted to concentration units by interpolation on a calibration curve. For this purpose a sample of Ekofisk crude oil was distilled to about 200°C, when approximately 40% of the original weight had dissapeared. The calibration curve of chromatogram area, between C_{14} and C_{22} as for the unknown samples, versus injected amount was made from five different samples of this reference oil in dichloromethane.

For determination of selected aromatics, known amounts of fluorene and anthracene, which are present in Ekofisk crude in only trace amounts relative to the other aromatics, were added to the aliquot which was withdrawn from the water extract. The dichloromethane was then evaporated just to dryness as desctibed above, the residue dissolved in approximately 15 µl carbon disulfide, and 0.1 µl of this solution was chromatographed on a 20 m SE-54 glass capillary column, (from Jäeggi, Trogen, Switzerland), with helium as carrier gas, at 2 ml/min. The oven was programmed from 100 to 230°C, at 6°/min. The column was connected by a 30 cm platinum capillary tube without separator directly to the ion chamber of a Finnigan 3200 mass spectrometer. The mass fragmentographic analysis was achieved by tuning the quadropole analyser of the instrument to detect the ions with mass 128, 141 and 170 during the first 4.4 minutes after the temperature program of the chromatograph oven was started. Thereafter the ions with mass 141, 166 and 170 were detected during the next

6.8 minutes, following by 3.2 minutes for 178, 184 and 198 ions and finally 3.4 minutes for the ions 206, 212 and 226. These mass units represent the molecular ions of respectively: 128 - naphthalene, 141 - methylnaphthalene minus one mass unit and dimethylnaphthalene minus 15 mass units, 166 - fluorene, 170 - trimethylnaphthalene, 178 - phenenthrene and anthracene, 184 - dibenzothiophene, 192 - methylphenenthrene, 198 - methyldibenzothiophene, 206 dimethyl-phenanthrene, 212 - dimethyldibenzothiophene and 226 - trimethyldibenzothiophene. The various peaks were integrated after substraction of the background signal. Each area was corrected according to the percentage the molecular ions make out of the total ion current which results from fragmentation of each specific compound. The corrected areas were then converted to concentration units by comparison with the internal standards. The quantification is based on the assumption that all compounds give the same total ion current per unit weight.

RESULTS AND DISCUSSION

Gas chromatograms of extracts of water collected in the same area north of the Bravo platform, Fig. 2, at three different stages of the incident are shown in Fig. 3 together with a chromatogram of oil retrieved from the surface. The only chromatogram which resembles the one of the oil is of the sample from the day before the blowout was stopped when oil was present in the area as slicks, patches or thin film. The chromatogram has similar alkane pattern and unresolved complex mixture (UCM) as the one of the oil, although the maximum of both is displaced somewhat towards components of lower volatility. This implies that the oil appeared in the water as oil-in-water emulsion. In the vicinity of the Bravo platform significant amounts of this, i.e. between approximately 100 µg/l and 400 µg/l were detected on some of the stations of the first cruise and all stations on the second cruise, as shown in Fig. 2. The emulsion could only be detected during the blowout and the first days afterwards and only in areas with relatively fresh oil on the surface. The total area were this was the case is shown in Fig. 4.

The absence of alkane pattern in the other two chromatograms in Fig. 3 indicates that oil as such was not present in the water when the two samples were collected. The first of these was from the second day of the blowout before any oil had reached the area due to northwesterly wind. The other was taken 14 days after the blowout was stopped with no oil remaining in the area. However, both chromatograms have an UCM.

The experience from a long range of samples of both polluted and unpolluted seawater is that extraction with dichloromethane, evaporation of the solvent and direct gas chromatography always gives an UCM. In many instances these UCM have a maximum above C_{25}, and the influence from this can be reduced by only using the part of the chromatogram between C_{14} and C_{22} for quantification. Nevertheless, the background values from naturally occurring compounds make up between 20 and 40 µg/l. It is thus obvious that this method for determination of oil pollution in the sea has to be used with great care. In the present case only chromatograms with typical alkane pattern and amounts exceeding 100 µg/l were taken into consideration.

As demonstrated by T. Audunson in the previous paper, the oil on the surface was distributed over a much larger area than the distribution of oil-in-water emulsion indicated in Fig. 4. A chemical impact of soluble components of the oil should therefore be expected over a larger area. The total hydrocarbon chromatographic method (THC) was insufficient in detecting this impact. It was necessary to use an analytical method which selectively could detect the components in question.

The aromatic hydrocarbons are among the most water soluble components of crude oil. They are also considered to be the most toxic. In the present investigation the interest was focused on naphthalene, phenanthrene and dibenzothiophene and their alkyl derivatives with up to three carbon atoms, in the following designated NPD. These are abundant in Ekofisk crude oil, i.e. 1.8% by weight. They constitute between 1 and 2% of most crude oils, and in distillates like fuel oil and Bunker C they account for an even higher percentage. They do not occur naturally in the marine environment and their presence in a sample indicate pollution by oil.

By the use of a mass spectrometer as detector on a gas chromatograph in the so-called selected ion monitoring technique (SIM), the NPD's could be quantitatively determined even in the presence of a large excess of naturally occurring components. It is impossible to completely eliminate contamination during sampling, workup and analysis, and the procedural blanks normally contain NPD's equivalent to 0.01 - 0.02 µg/l. Accordingly, amounts in excess of 0.05 µg/l were considered traces of pollution and amounts in excess of 0.1 µg/l positive evidence for pollution by oil.

It has been common practice to extrapolate the results of the analysis of a single or a few components or parameters to total oil by comparison with a reference oil. Since the NPD's are selectively accomodated to the water and in this manner enriched by an unknown and variable factor relative to most of the other components in the polluting oil it is impossible to deduce the total amount of petroleum hydrocarbons present in the water from the NPD values. These values are therefore used as such in the following description of the distribution of the pollution.

The observation fall into three stages. The first was during and immediately after the blowout when fresh oil was on the surface and oil-in-water emulsion was observed in the water. The second was two weeks after the blowout was stopped when the remaining oil was distributed north of Ekofisk in the form of small lumps. The third stage was 4 - 6 weeks after closure with the small amount of remaining oil on the surface located south of Ekofisk.

The distribution of the NPD's during the three stages is shown in Fig. 4. In the first stage the amounts of NPD's reached 8 µg/l in the close vicinity of Bravo where high concentrations of emulsion also was observed. In the outer parts of the polluted area the concentrations were approximately 0.1 µg/l. The situation was illustrated by a transect of 4 stations from Bravo towards northeast in the direction of the drift of the oil at that time. Four nautical miles (n.m.)

from Bravo 4.1 μg/l of NPD's were detected and appr. 250 μg/l. of oil-in-water emulsion. Eleven n.m. away there was 0.38 μg/l NPD's and the amount of the emulsion was around the detection limit of approximately 100 μg/l. Thirty n.m. to northeast was still found significant amounts of NPD, 0.13 μg/l, but no emulsion, and finally 48 n.m. away NPD was also down to blank values. During the first stage water was collected from both 1 and 5 m depth on several stations, but no gradient was observed in the concentrations of emulsion and NPD.

The widest detectable distribution of the polluted water was around 2 weeks after capping of the well with concentrations of NPD's ranging from 0.4 μg/l in the vicinity of Bravo down to trace amounts of 0.05 μg/l at the outskirt of the area indicated in Fig. 4. Samples from 1, 5 and 10 m depth on several stations showed no detectable gradient. In this stage the remaining oil was observed as dense patches of small lumps in an area north of Ekofisk indicated in Fig. 4. Several samples of water collected in the area gave no positive evidence of NPD's in the water column beneath the oil lumps.

In the third stage 4 - 6 weeks after the blowout was stopped samples were collected along one section between Norway and Denmark and one section between Norway and the Shetland Islands, as well as in the central North Sea as shown in Figs. 1 and 4. The sections go through coastal currents into which polluted water from the central North Sea might be transported by wind and tide. None of these samples showed any evidence of petroleum hydrocarbons. However, four of the samples taken south of Ekofisk contained significant amounts of NPD's. Oil lumps were also found in this area.

The relative compositions of the NPD's given in the table demonstrate a significant reduction of total naphthalenes and corresponding increase in phenanthrenes and dibenzothiophenes. The relative increase was largest for the dibenzothiophenes, appr. 3 times versus appr. 1/2 time for the phenanthrenes. This suggest a slower degradation of the dibenzothiophenes. By using the relative amounts of the various NPD's in the samples and taking the trend of the change by time, as demonstrated in the table, into consideration, the four water samples as well as some of the oil lumps from the surface could tentatively be related to a non-Bravo origin.

It is therefore concluded that after 4 - 6 weeks the level of petroleum hydrocarbons in the water was very low and beyond detection due to efficient weathering.

Relative amounts (% of total NPD) of the individual naphthalenes, phenanthrenes and dibenzothiophenes found in the water samples near the Bravo platform. First column is average of 25 samples collected during the blowout, second column is average of 11 sample collected 13 days after the blowout was stopped.

N	6.5 ± 1.6	5.0 ± 1.4
MN	20.2 ± 3.0	10.1 ± 1.2
DMN	40.3 ± 2.6	36.2 ± 3.1
TNM	16.0 ± 1.5	19.1 ± 2.7
N	83.7 ± 2.8	70.5 ± 5.1
P	2.6 ± 0.8	3.7 ± 0.6
MP	5.2 ± 1.2	8.9 ± 1.2
DMP	4.8 ± 1.2	6.8 ± 1.5
P	12.6 ± 2.2	19.4 ± 2.7
D	0.25 ± 0.09	0.9 ± 0.2
MD	1.1 ± 0.3	3.5 ± 0.7
DMD	1.6 ± 0.8	4.5 ± 1.8
TMD	0.7 ± 0.26	1.7 ± 1.2
D	3.6 ± 1.1	10.2 ± 3.8

Abbreviations: N - naphthalene, MN - methylnaphthalene, DMN - dimethyl- (or ethyl-) naphthalene, TMN - trimethyl- (or methyl, etyl- or propyl-) naphthalene, and correspondingly for the phenanthrenes (P) and dibenzothiophenes (D).

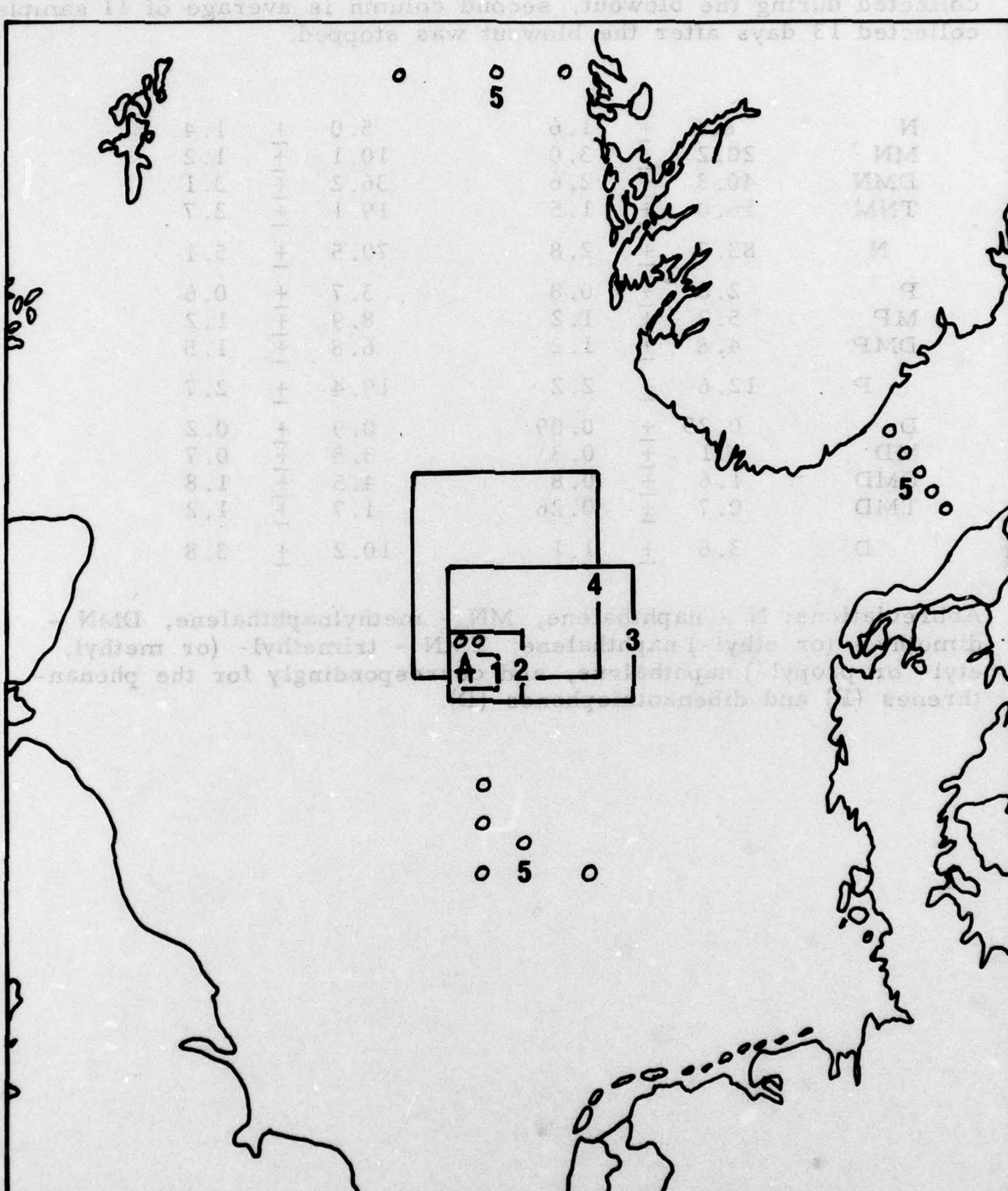

Fig. 1 Area covered by the first four cruises and stations on the fifth cruise where water was sampled.

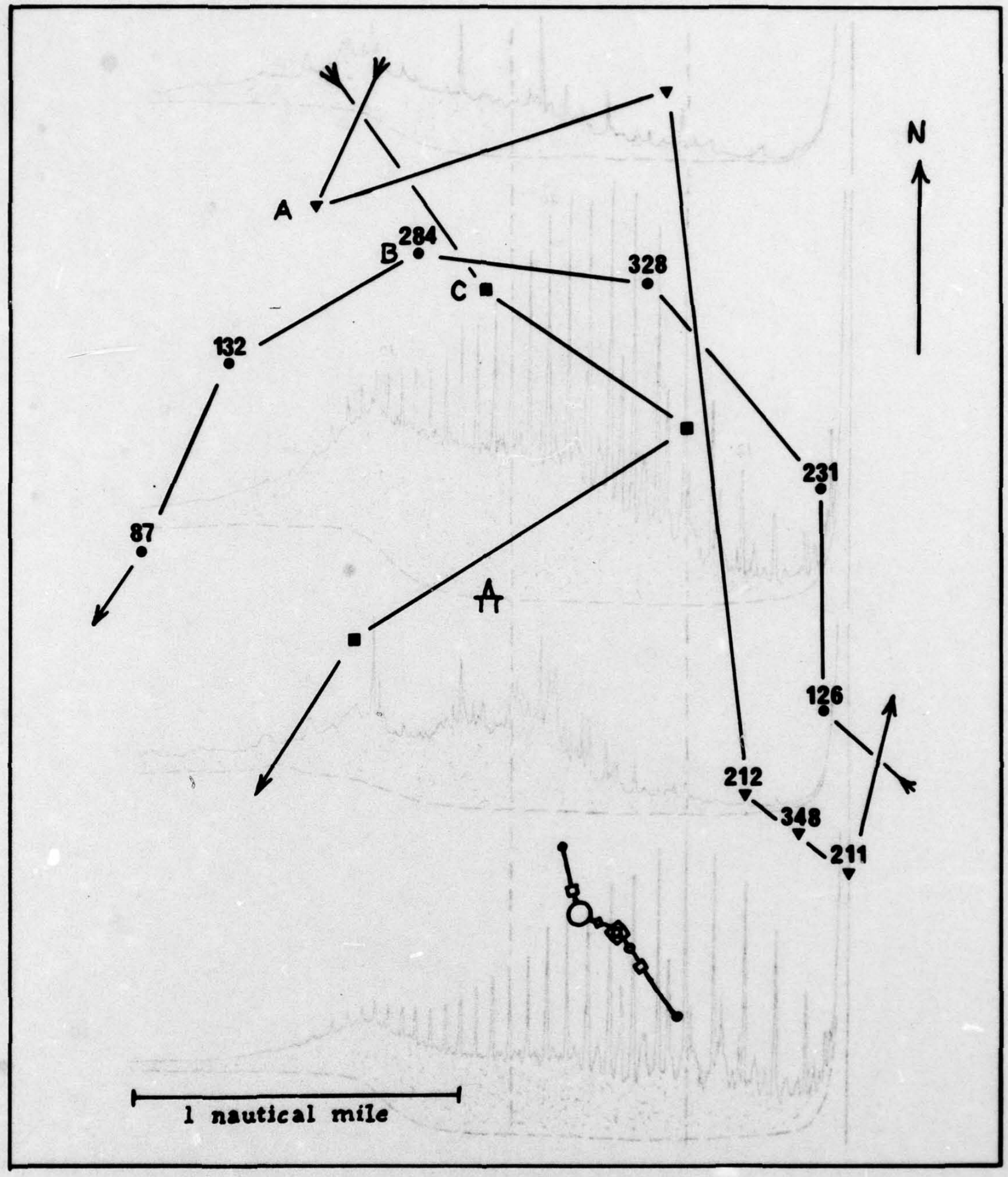

Fig. 2. Stations of three different cruises in the near surroundings of Bravo: ——▼—— KNM "Sleipner" April 24, ——●—— R/V "G.O. Sars" April 29, ——■—— R/V "G.O. Sars" May 13. The numbers indicate the amount (μg/1) of oil-in-water emulsion. Gas chromatograms of extracts of water sampled at the stations marked with A, B and C are shown in Fig. 3.

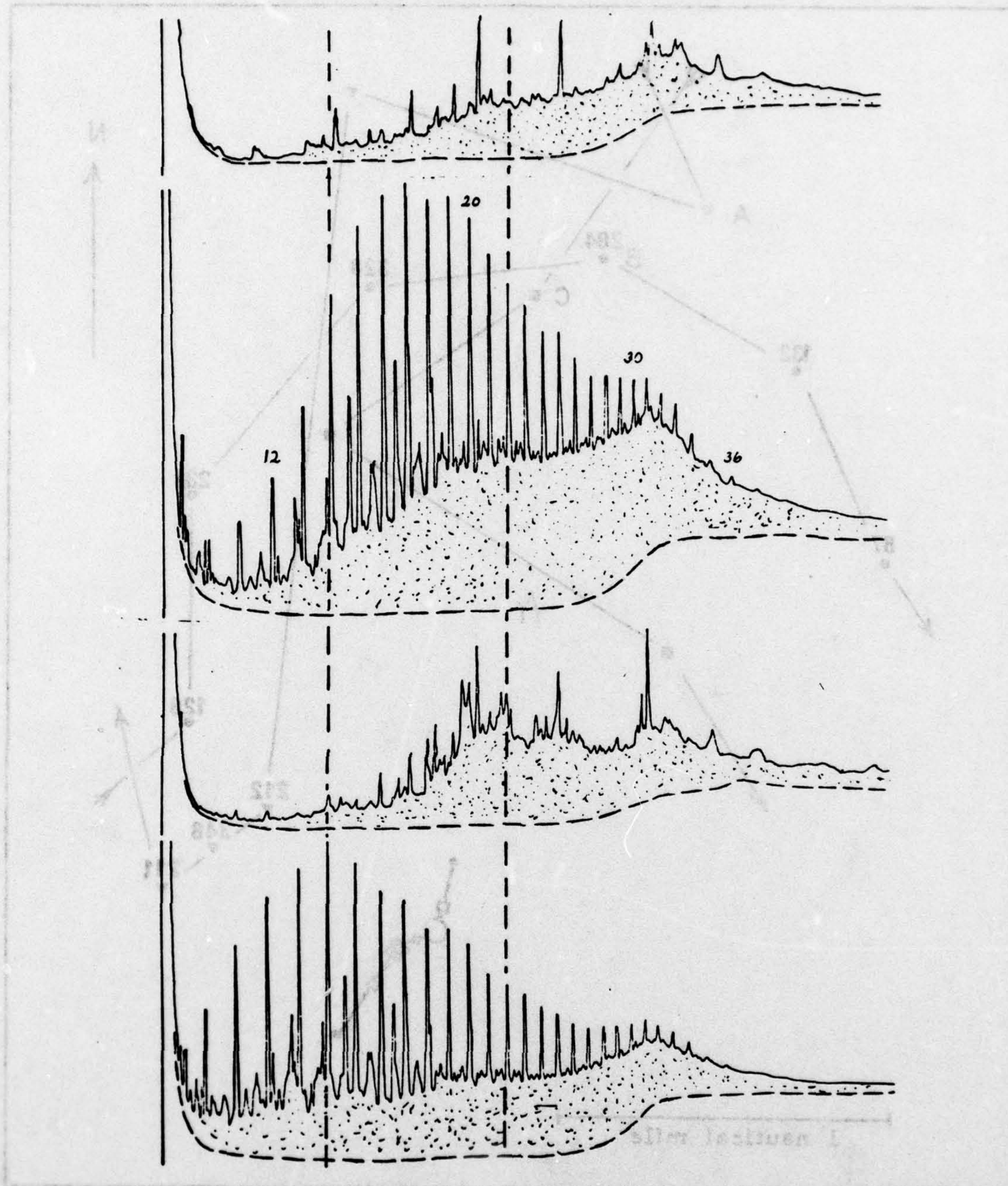

Fig. 3. Gas chromatograms from a packed column with flame ionization detector of, from the top: extracts of water sampled at the stations marked A, B and C, respectively, and oil collected from a slick in the vicinity of Bravo on April 25.

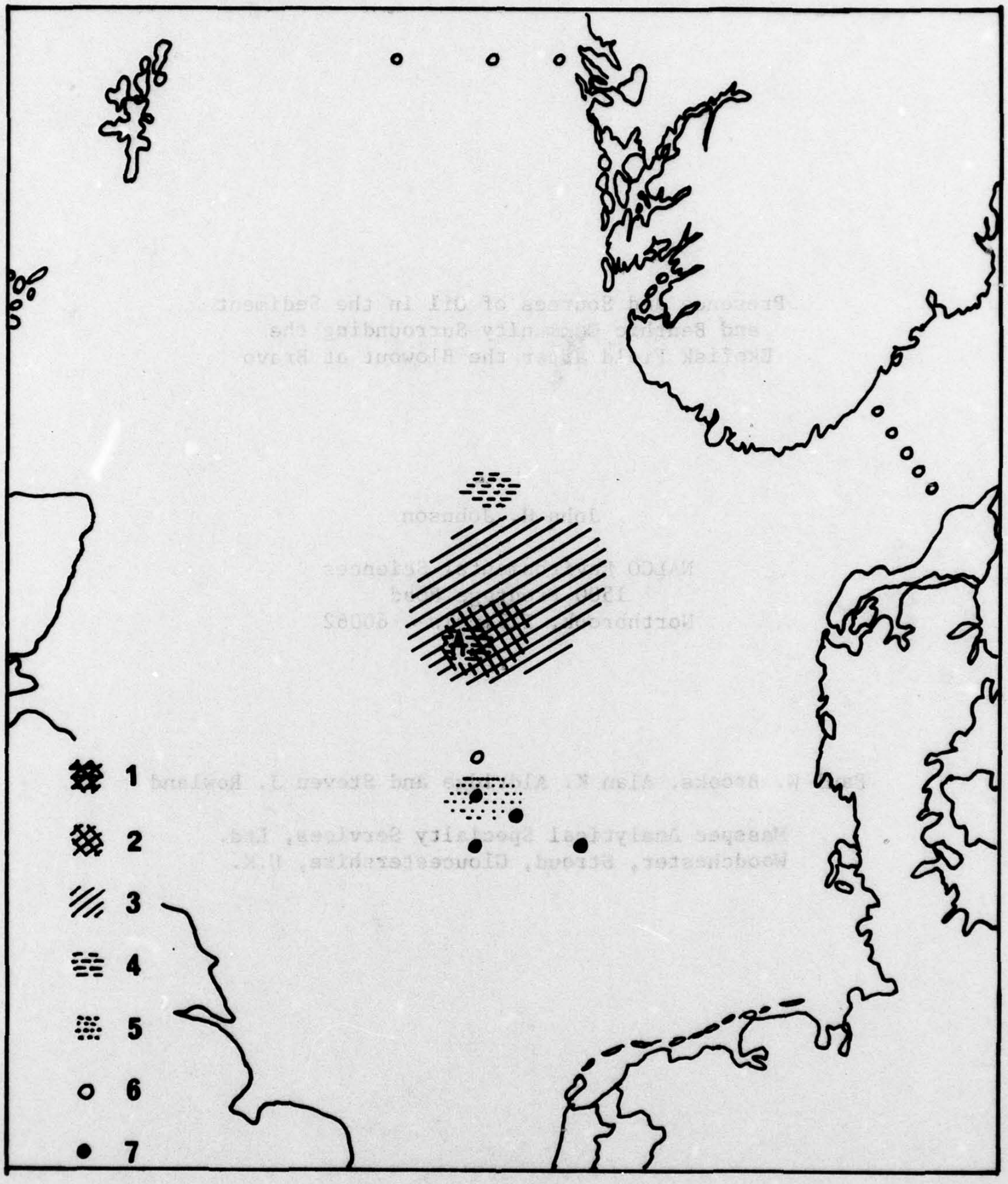

Fig. 4 Distribution of petroleum hydrocarbons. 1 Distribution of oil-in-water emulsion during the blowout. 2 Distribution of NPD during and immediately after the blowout, first stage. 3 Distribution of NPD two weeks after the blowout, second stage. 4 Remaining oil on the surface two weeks after the blowout. 5 Remaining oil on the surface 4 - 6 weeks after the blowout. 6 Stations where NPD could not be detected 4 - 6 weeks after the blowout (two stations of this category immediately north of Bravo are not shown). 7 Stations with significant amounts of NPD in the water 5 weeks after the blowout.

Presence and Sources of Oil in the Sediment and Benthic Community Surrounding the Ekofisk Field after the Blowout at Bravo

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SUMMARY

NALCO Environmental Sciences, at the request of the Phillips Petroleum Company, has undertaken an extensive environmental study to define possible contamination of the aquatic ecosystem by oil released during the Bravo blowout. Sediment and benthic samples, collected during the first phase of this study from a 100 mile square grid centered around the Ekofisk platform, have been processed to their isolate hydrocarbon fractions. These were analyzed by gas chromatography and gas chromatography/mass spectrometry to determine the presence of hydrocarbons attributable to Bravo crude. The analytical data obtained indicated hydrocarbons which could be linked to Bravo crude were present in the sediments and benthic samples at levels relatively low in comparison to hydrocarbons from other natural and manmade sources.

INTRODUCTION

The blowout at the Ekofisk Bravo Platform in April 1977 released approximately 15-22,000 tons of crude oil into the environment (Berge 1977). NALCO Environmental Sciences, at the request of Phillips Petroleum Company, initiated an interdisciplinary study in May 1977 to define the effects of the spilled oil on the aquatic ecosystem. One aspect of the study is to determine the levels of Bravo crude oil in sediments, organisms and the water column. In this paper, we are reporting on the levels of hydrocarbons attributable to Bravo crude found in sediments and benthic samples collected during the first of three sampling events.

Hydrocarbons in sediment and benthic samples could arise from numerous sources other than Bravo crude: such as natural biological processes, combustion products, chronic long-term oil contamination, discrete oil spills, and degraded oils. The complexity of the sample matrix and the anticipated low levels of hydrocarbons including those of residual Bravo crude dictated a series of techniques for the separation of hydrocarbon fractions from the sample matrix, resolution of these fractions into individual component compounds, and finally measurement of hydrocarbons attributable to Bravo crude.

Thin layer chromatography (TLC) was used to separate hydrocarbons from other organic compounds. The resulting hydrocarbon fractions were analyzed via gas chromatography/ flame ionization detection

(GC/FID) and gas chromatography/mass spectrometry (GC/MS) to identify and quantify individual compounds. Chromatograms from each sample were interpreted for indications of Bravo crude using a series of established and some novel criteria.

MATERIALS AND METHODS

Field Procedures

Single sediment samples were collected during May 1977 at each of 41 locations within a 100 mile square grid as shown in Figure 1. Samples were collected using a Smith-McIntyre grab which had been cleaned with aqueous detergent and subsequently washed with carbon tetrachloride (CCl_4). Samples were emptied from the grab into a stainless steel bucket and then transferred to a length of 2-inch diameter polycarbonate tubing with a stainless steel spoon. The tubing was closed with aluminum foil washed with CCl_4. All utensils and supplies which came into contact with the samples were rinsed with CCl_4 and then air dried immediately prior to use. Benthic organisms listed in Table 1 were collected from the indicated locations and wrapped in CCl_4 washed aluminum foil. All samples were immediately frozen, packed in coolers with dry ice and transported to Masspec Analytical Specially Services Ltd. (England) for analysis of their hydrocarbon content.

Analytical Procedures

Extraction and Fractionation: Sediment samples were locally thawed and then extruded from the polycarbonate tubes. The first inch of sediment was discarded and one half (corresponding to 300 g dry weight) of the remainder was taken for extraction and separation into 'alkyl' and 'aromatic' fractions as shown in Figure 2. Selected 'alkyl' fractions were further separated into saturated and unsaturated components via silver nitrate/silica gel thin layer chromatography (Ag^+/TLC) for analysis to aid confirmation of the assignment of hydrocarbon components.

Aqueous liquor from mussel, clam, and urchin samples was discarded and the flesh retained for extraction. Flesh was homogenized and the hydrocarbons extracted for and separated into 'alkyl' and 'aromatic' fractions as shown in Figure 2.

Gas Chromatography: Each hydrocarbon fraction was analyzed by capillary collumn gas chromatography/flame ionization detection for indications of contamination by petroleum products. 'Alkyl' fractions from both sediments and organisms were analyzed by GC/FID using a 30m x 0.5mm glass support coated open tubular (SCOT) column coated with OV-1 under these conditions: temperature programmed from 80-260^{o}C at 6^{o}/min, helium carrier at 2 ml/ min. 'Aromatic' fractions were analyzed by GC/FID with a 20m x 0.25mm glass column coated with OV-1; temperature linear programmed from 60-250^{o} at 6^{o}/min with helium carrier at 2 ml/min.

Samples which showed possible contamination by petrogenic hydrocarbons were subsequently analyzed by computerized gas chromatography/mass spectrometry (GC/MS) using a) Alkyl: 20m x 0.5 mm OV1 and b) Aromatic:

30 m x 0.25 mm OV-101 Columns; temperature linear programmed from 80-250^o at 4^o/min with helium carrier gas at 2 ml/min.

Reference hydrocarbon standards and Bravo crude were analyzed for purposes of instrument calibration and identification of hydrocarbon components in the samples. A known amount of Bravo crude was added to an aliquot of sediment and analyzed as above to compare with samples for purposes of quality control. Reagent and procedural blank experiments were performed periodically and showed insignificant contamination through workup. Less than 100 picgrams (10^{-12} g) of hydrocarbons was observed in any blank.

RESULTS

Gas Chromatography/Flame Ionization Detection

The GC/FID traces for the 'alkyl' fractions derived from sediment samples were found to be quite complex as illustrated by the chromatogram obtained from location 11 (Figure 3A). Each sample chromatogram was evaluated for indications of the presence of Bravo crude by use of the criteria listed below.

1. Ratios of $\underline{n}$-C_{18}/$\underline{n}$-C_{29} and $\underline{n}$-C_{27}/$\underline{n}$-C_{26}: These ratios measure the level of the contemporary spill vs. natural biological input. Aliphatic hydrocarbons $\underline{n}$-C_{18} and $\underline{n}$-C_{29} are major and minor components respectively of Bravo crude as shown in Figure 4 whereas $\underline{n}$-C_{29} is representative of the predominance of odd numbered alkanes from biological sources (Hardy et al. 1977; Clark and Blumer 1967). Thus the larger the $\underline{n}$-C_{18}/$\underline{n}$-C_{29} ratio the greater the contemporary crude oil input in relation to the naturally derived hydrocarbon background (Whittle et al. 1977). Most chromatograms exhibited major peaks greater than $\underline{n}$-C_{20} as with location 11 (Figure 3A). The low even/odd ratio as exhibited with samples from location 11 is expected for 'natural' $\underline{n}$-alkanes (Farrington and Meyers 1975; Wehmeller and Lethen 1975).

Aliphatic hydrocarbons $\underline{n}$-C_{27} and $\underline{n}$-C_{26} from biological sources would show a marked odd/even predominance, whereas hydrocarbons from an oil spill would be expected to contain similar levels of $\underline{n}$-C_{27} and $\underline{n}$-C_{26}. When Bravo crude was added to the sediment from location 11, the concentrations of $\underline{n}$-C_{26} and $\underline{n}$-C_{27} were found to be similar (Figure 3B). These similar concentrations would be expected in samples contaminated by Bravo crude.

2. Hump/(hump + $\underline{n}$-C_{29}): An unresolved mixture of hydrocarbons has been observed in gas chromatograms of hydrocarbon fractions in other recent sediments as a 'hump' (Keizer 1978; Farrington and Trip 1977; Clark and Finley 1973). The hump is caused by hydrocarbons which are not resolved by the gas chromatograph and are the result of microbial degradation of fossil fuels (Blumer et al. 1973) and biogenic hydrocarbons (Farrington and Quinn 1973). The hump/ (hump + $\underline{n}$-C_{29}) function compares

the unresolved overlapping homologus branched and cyclic components with hydrocarbons of natural origin. This ratio reflects the balance between chronic pollution and natural hydrocarbons ($\underline{n}$-C_{29}).

In this context and, indeed, throughout this discussion, the term chronic and chronic long-term have been used to mean inputs prior to the blowout at Bravo. We consider that the paraffinic components of Bravo crude would not have been significantly degraded prior to sampling, whereas inputs of already degraded petroleums will be detected by GC/FID analysis as the 'hump'.

3. ppm Bravo crude based on $\underline{n}$-C_{18}: This parameter is calculated with the GC/FID peak height of $\underline{n}$-C_{18} extracted from the spiked sediment from location 11 to which 18 parts per million (ppm) of crude was added (compare Figures 3A and 3B with Figure 4). The $\underline{n}$-C_{18} peak was chosen as it has an even carbon number not of biological origin, and it is not lost in sample work up procedures (60% recovery). This peak is compared with a $\underline{n}$-C_{18} peak height of the sample in question, and corrected for sediment dry weight and proportion of sample injected.

$$ppm_u = \frac{height_u}{height_s} \times \frac{volume_s}{volume_u} \times \frac{weight_s}{weight_u} \times ppm_s$$

u = unknown
s = standard

The assumptions involved here is that $\underline{n}$-C_{18} is a measure of oil pollution by Bravo crude and that previously deposited $\underline{n}$-C_{18} has been degraded (Baily 1973).

Evaluation of the gas chromatograms obtained using the above criteria indicated that sediment hydrocarbons from a contemporary spill were low in abundance compared to those from other sources. The $\underline{n}$-C_{18}/ $\underline{n}$-C_{29} ratio indicated Bravo crude in sediments at locations 13, 26, 29, 31, 48, 51, 79, 97, and clam location 93. Examination of the $\underline{n}$-C_{27}/ $\underline{n}$-C_{26} ratios indicates higher molecular weight alkanes were mainly from biological sources. The lack of dramatic differences in the hump/(hump + $\underline{n}$-C_{29}) values as shown in Figure 5 showed the majority of hydrocarbons in the area of Ekofisk were those from long term sources. Estimation of crude based on $\underline{n}$-C_{18} shows levels of Bravo crude were above 5 ppm at sediment locations 13, 31, 51, 56, 57, 79, and 91. However, no location was observed to contain greater than 8 ppm (Figure 6).

Most sample sites east of the Bravo platform had significantly higher concentrations of degraded hydrocarbons than those to the west as illustrated by the hump/(hump + $\underline{n}$-C_{29}) criteria. The $\underline{n}$-C_{18} criterion indicated two areas of concern on either side of the Bravo Site, reflecting the drift of oil as reported by the International Council for the Exploration of the Sea (Ljoen et al. 1977). This may have reflected the path of the spilled oil and may also have indicated the occurrence of long term chronic deposition of hydrocarbons from Ekofisk and other drilling operations (Figure 1). The above data indicated that most of the sites analyzed were contaminated to an extent by chronic long term spillage possibly fromm natural seeps. No sample was observed to contain

greater than 8 ppm based on $\underline{n}$-C_{18}. Thus the levels of oil which could be attributed to that from Bravo were relatively low for all locations.

Benthic organisms were chosen to serve as indicators of marine pollution since accumulated petroleum components should be abundant relative to biolipids (Lee 1977; Di Salvo et al. 1975; Goldberg 1975). Only the urchin at location 17 showed substantial amounts of $\underline{n}$-alkanes. The complex hump of unresolved components indicating biodegraded crude was observed in mussels from locations 57 and 93; urchins at 17, 36, 46, 56 and 57; and a clam at 39. Since conclusions from the above criteria were complicated by the possibility of degradation before the oil could reach the ocean floor, fractions which indicated the highest amount of Bravo crude were subjected to further GC/MS analysis for additional characterization.

Gas Chromatography/Mass Spectrometry - Alkyl Compounds

Samples which showed the highest levels of aliphatic hydrocarbons by the GC/FID criteria described above were examined by GC/MS. Data for parameters listed below were collected for use as indicators of petroleum contamination.

M/E 85: This ion is prominent in the spectra of acyclic alkanes (McLafferty 1967). Alkanes in the low molecular weight range are not normally abundant component hydrocarbons of most biological systems, with the exception of some species of algae and bacteria (Clark and Blumer 1967). However, they are abundant components of most crude oils which have not been extensively biodegraded, such as crude from the Bravo (Figure 7A). Further, there is normally no predominance of odd carbon number over even. The occurrence of high abundances of low molecular weight $\underline{n}$-alkanes having no carbon preference index (CPI) indicated contemporary crude oil pollution (Wehmeller and Lethan 1975; Miller 1973). The high molecular weight region includes alkanes of carbon number ca. $\underline{n}$-C_{20} and above. These alkanes are normally components of biological species, especially those of higher plants (Farrington and Meyers 1975). In such fractions the alkanes normally maximize at C_{27}, C_{29}, or C_{31} and show a pronounced odd/even CPI.

M/E 83: This ion is used to analyze the cyclohexyl alkanes content. The series of cyclic alkanes extends from ca. $\underline{n}$-C_{12} to $\underline{n}$-C_{28} and Maximizing at ca. $\underline{n}$-C_{18}. This series is expected in crude oils where extensive biodegradation has not taken place. Such a series is observed in Bravo crude (Figure 7B). If extensive biodegradation has taken place in crude deposited on sediment, this series is no longer apparent but instead a complex 'hump' of unresolved compounds is observed as with location 11 (Figure 3A).

M/E 217: This ion is used to monitor the Steroidal alkanes. Steranes are present in minor amounts in most crude oils including that from Bravo (Figure 8A) but have not been reported to be present in unpolluted recent sediments examined to date. The relative distribution of individual steranes differs significantly with the origin of oil (Dastillung and Albrecht 1976). Hence, the distribution of steranes found in the samples under study have been compared to Bravo crude.

M/E 191: This ion is characteristic and intense in the spectra of many di-and triterpenoid alkanes. This ion is used to monitor Pentacyclic triterpanes of the hopane skeleton appear predominantly in chromatograms of crude oils. They are more resistant to biological degradation than acyclic alkanes and other cyclic alkanes (Dastillung and Albrecht 1976). Figure 8B shows the peak assignments of the major triterpanes in the m/e 191 fragmentograms, based on retention times and full mass spectral data (Van Dorsselaer et al. 1974). Triterpenes studied here reflect those described earlier for other North Sea fields (Pym et al. 1975). Hopane triterpanes having the 17αH-stereochemistry (more stable) and the 17βH-stereochemistry (less stable) were observed in recent unpolluted sediments (Ensminger et al. 1974; Van Dorsselaer et al. 1974).

In Bravo crude only hopanes having the more stable 17αH-stereochemistry have been detected. 17βH-hopanes with carbon numbers of n-C_{31} to n-C_{35} may also exist as two diastereoisomers at C-22 which are separable by capillary GC/FID and GC/MS. In North Sea crude oils, the first eluting isomer (C) predominates slightly over the second isomer (D), as is the case with Bravo crude (Figure 8B). However, in hydrocarbon fractions from unpolluted sediments examined to date, the second eluting isomer (D) of the C_{31} 17αH-hopane doublet has predominanted (Brooks et al. 1975). Therefore a measure of crude oil contribution versus natural hydrocarbon contribution may be made by the ratio of the first eluting/second eluting 17αH-C_{31} homohopanes (C/D). This ratio is >1 with high crude oil contribution and 1 with low crude oil contribution. The first eluting 17αH-C_{31} hopane (crude oil characteristic)/17βH-C_{31} hopane contribution (natural contribution) (C/G) is >1 with high crude oil contribution, and $\geq$1 for low or nonexistent crude oil contribution. Thus the greater the value of this ratio, the larger relative contribution of fossil fuel hydrocarbons. The 17β-Homohopane(G) was found to be negligible in Bravo crude.

Major features observed in the organism and sediment fragmentograms for m/e 85, 83, 217 and 191 were evaluated for the presence of Bravo crude. An evaluation of these criteria is summarized in Table 2. The occurrence of low molecular weight n-alkanes for sediment locations 13, 16, 26, 31, 35, 51, 56, 59, 79, 93, 97 and clam location 93 having low carbon preference index (CPI) indicated contemperary crude oil pollution (Wehmeller and Lethen 1975; Miller 1973). Virtually all samples showed significant amounts of high (>C_{20}) molecular weight hydrocarbons with appreciable CPI, which in the main corraborated the n-C_{18}/n-C-29 results. A homologous series was present in the m/e 83 framentograms for locations 13, 16, 26 and clam location 29 only. In addition, a pronounced hump was observed for locations 13, 56, and 57 indicating the presence of degraded petroleum from a chronic input. The highest contributions of steroidal alkanes (m/e 217) similar to Bravo crude were found for sediment locations 28, 48, 57, 79; and possible similarities were observed for sediment locations 13, TOR, 51, 53, 56 and mussel location 57and clam location 29. Complex distributions were observed for all locations. Triterpanes as observed in the m/e 191 fragmentogram were observed for all sediment locations investigated. The C/D hopane ratio indicates Bravo crude in sediments from locations 26, 28 and TOR, mussel station 57, and clam stations 29, and 39. Values for the C/G parameter indicated fossil fuel hydrocarbons at all stations listed in Table 2.

Gas Chromatography/Mass Spectrometry (GC/MS) - Aromatic Compounds

GC/MS data of selected aromatic fractions was also used to detect Bravo crude. The presence of long term input from air pollution and other sources serves to make interpretation of fragmentograms more difficult. Seven ions were chosen to monitor specific compounds for purposes of identifying Bravo crude in the presence of other aromatic contamination.

M/E 92: A homologous series of alkylbenzenes is present in aromatic fractions of unaltered crudes (Aldrige et al. 1976). They are the most readily degraded of those aromatic species present in unaltered crudes and their presence therefore serves as an indication of contamination by substantially unaltered crude with Bravo (Figure 9). In this marker function, they may be compared with n-alkanes and cyclic alkanes. However, alkylbenzenes are present in crudes at much lower levels than n-alkanes (of the order of $^1/100$ and less).

M/E 142 and M/E 156: Several alkylnapthalene isomers are present in high relative abundance in unaltered crude (Parker et al. 1976) as is the case with Bravo crude (Figure 10). They are not as readily degraded as alkyl benzenes and therefore serve as indicators of recent crude.

Polynuclear Aromatics: The major polynuclear aromatic (PNA) component of Bravo crude is phenanthrene (m/e 178, Figure 11). Other PNA's such as benzanthracenes and benzpyrenes as well as phenanthrene may be incorporated in sediments as a result of atmospheric fallout of the combustion products of fossil fuels and forest fires (Lunde and Bjorseth 1977; Hites 1976; McCleod et al. 1976; Lunde et al. 1976).

A summary of the GC/MS data is presented in Table 3. Alkyl benzenes are clearly observed in the 'aromatic' fraction of Bravo and were observed in low relative abundance for sediment locations 35, 38, 39, 53, and possibly 13, 53, 57, 79, and 97. Alkyl napthalenes were clearly observed in Bravo crude (Figure 10) and at low abundance for sediment locations 35, 57 and possibly 39. Dialkyl napthalenes were found in small amounts sediment locations 35, 57 and possibly 16, 39, 48, TOR (55), 79 and 93. Polynuclear aromatics were observed at low levels in all the sediment aromatic fractions and in significant amounts at mussel locations 13 and 57. The amounts of pheanthrene in the sediments (based on dry weight) are also given in Table 3. Levels ranged from 5 to 158 ppt (10^{-12} g) per gram of sediment. Highest levels were observed at sediment locations 51, 53 and TOR (55). Lowest levels were observed at sediment locations 28 and 31.

PNA's such as pyrenes, benzanthracenes and benzopyrenes (m/e 202, m/e 228, m/e 252 and) were similarly present in variable and often significant quantities in sediments. However these compounds were present in Bravo crude itself at levels approaching limits of detection (10^{-12} g/g). Aromatics of presumed crude oil origin were detected at few locations and were not conclusively concentrated in the Bravo area, whereas PNA's to include phenanthrene from probable atmospheric fallout (Lunde and Bjorseth 1977; and Lunde et al. 1976) were present at all locations at significant levels.

CONCLUSIONS

Sediments: Only small amounts of hydrocarbons were found in sediment samples. The hydrocarbons showed clear evidence of three principle components: natural aliphatic hydrocarbons of direct biological origin, fossil fuel hydrocarbons (partially degraded), and aromatic hydrocarbons principally of combustion product and possibly crude oil origin. All sediments contained less than eight ppm of hydrocarbons which might be of Bravo origin, with the majority containing less than 1 ppm. Furthermore, characterization of the hydrocarbons present in the samples studied indicated the content of oil which may be attributed to Bravo was low compared to that from other sources. Analysis of the data as summarized in Table 4 indicated that the amounts of degraded fossil fuel hydrocarbons were greater to the east of Bravo platform. Mass fragmentographic fingerprinting techniques suggested a number of sources of these pollutant hydrocarbons. Strongest similarities to Bravo crude were observed at three of the sediment locations (i.e. 28, 48 and 57). These locations are east and north of the Bravo well.

Organisms: Contamination of the benthic organisms analyzed was very low in all cases. Contamination by nonnatural hydrocarbons of Bravo origin was evident at locations 57 and 29 as shown in Table 4. These findings agree, in general, with those from the sediment studies.

The analytical data obtained indicates that in comparison to hydrocarbons from other natural and man made sources, hdyrocarbons linked to bravo crude were present in the sediments and benthic samples at levels relatively low.

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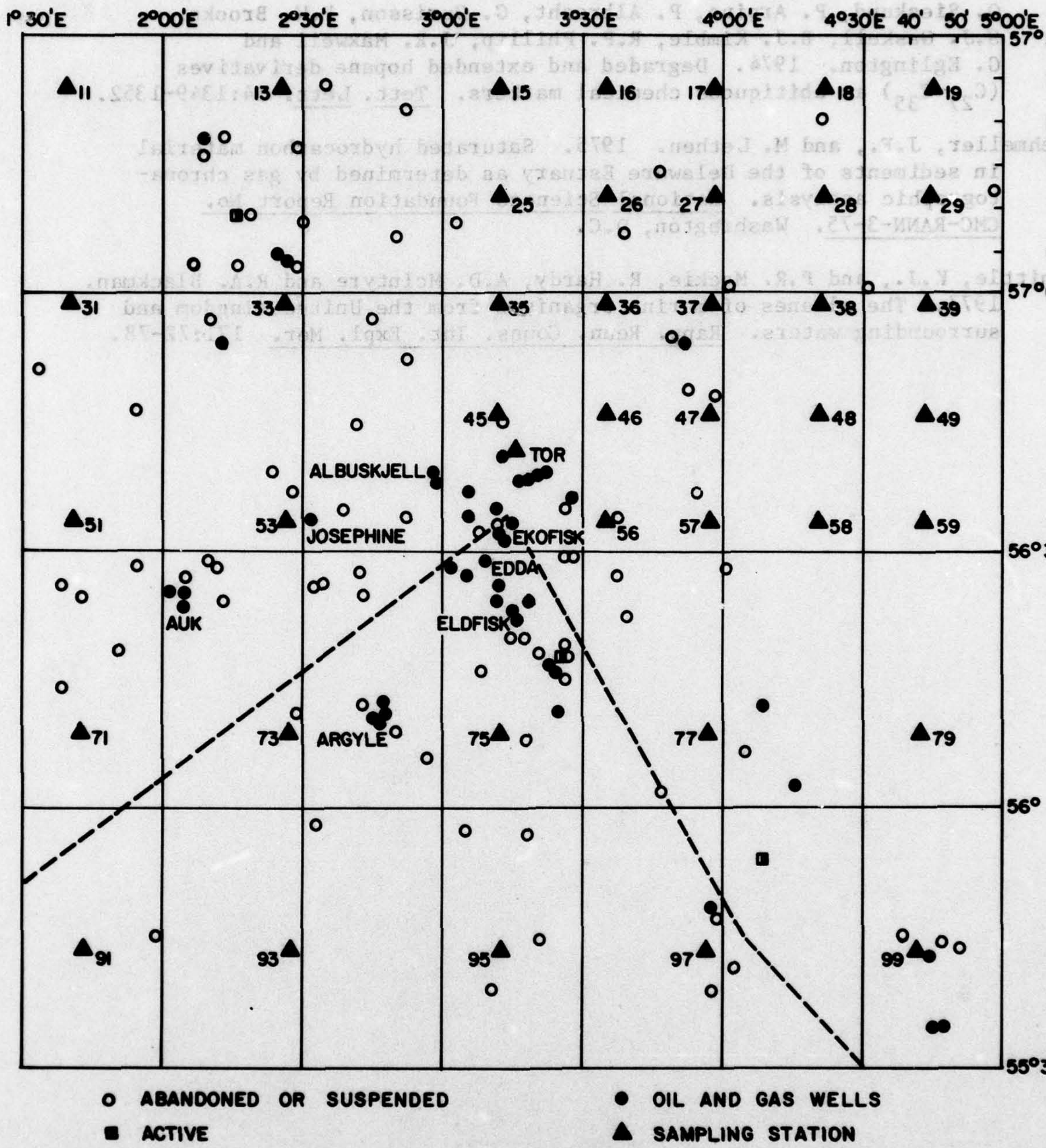


Figure 1. Exploration and drilling within the sampling grid. Adapted from "Northwestern Europe Offshore," June 1976.

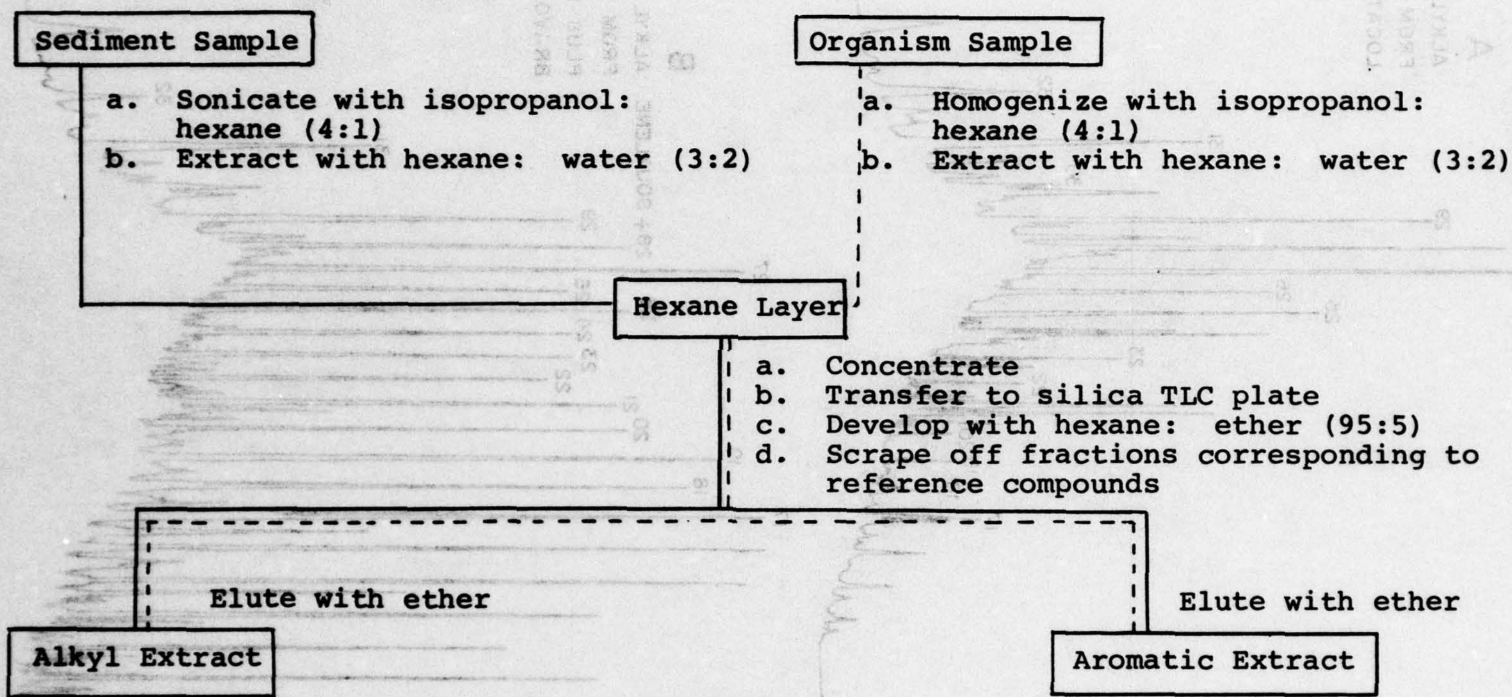
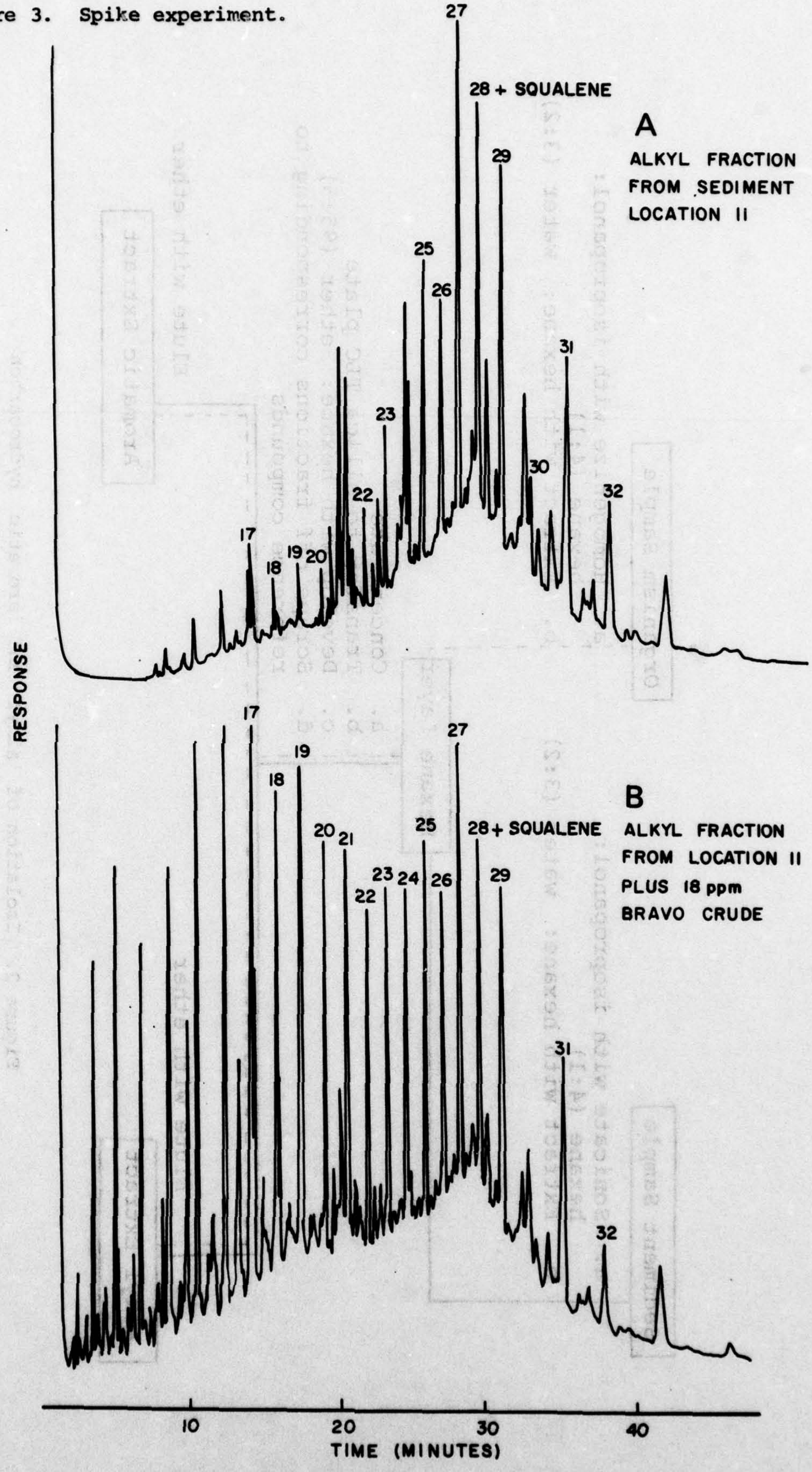
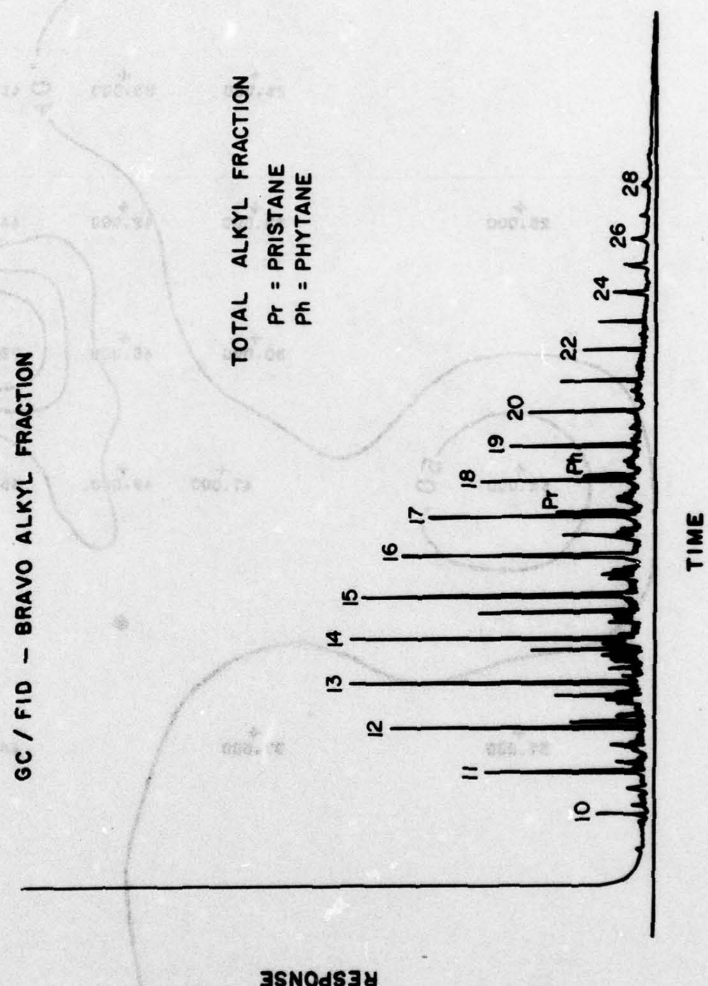


Figure 2. Isolation of 'alkyl' and 'aromatic' hydrocarbon fractions from sediments and benthic samples.

Figure 3. Spike experiment.




GC / FID – BRAVO ALKYL FRACTION
TOTAL ALKYL FRACTION
Pr : PRISTANE
Ph : PHYTANE
10
11
12
13
14
15
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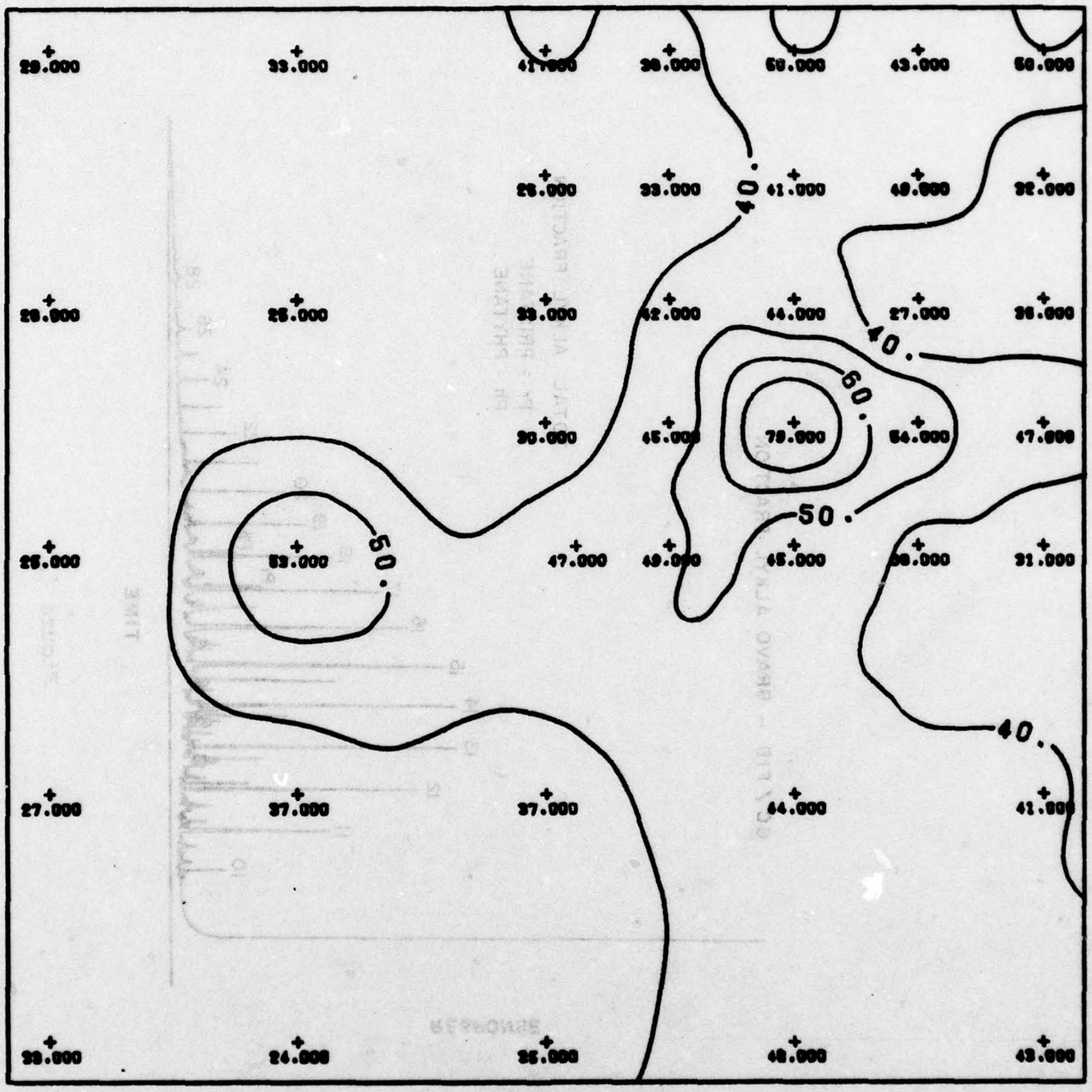
17
18
19
20
22
24
26
28
Pr
Ph
RESPONSE
TIME

Figure 4.



HUMP / HUMP+C29

Figure 5.

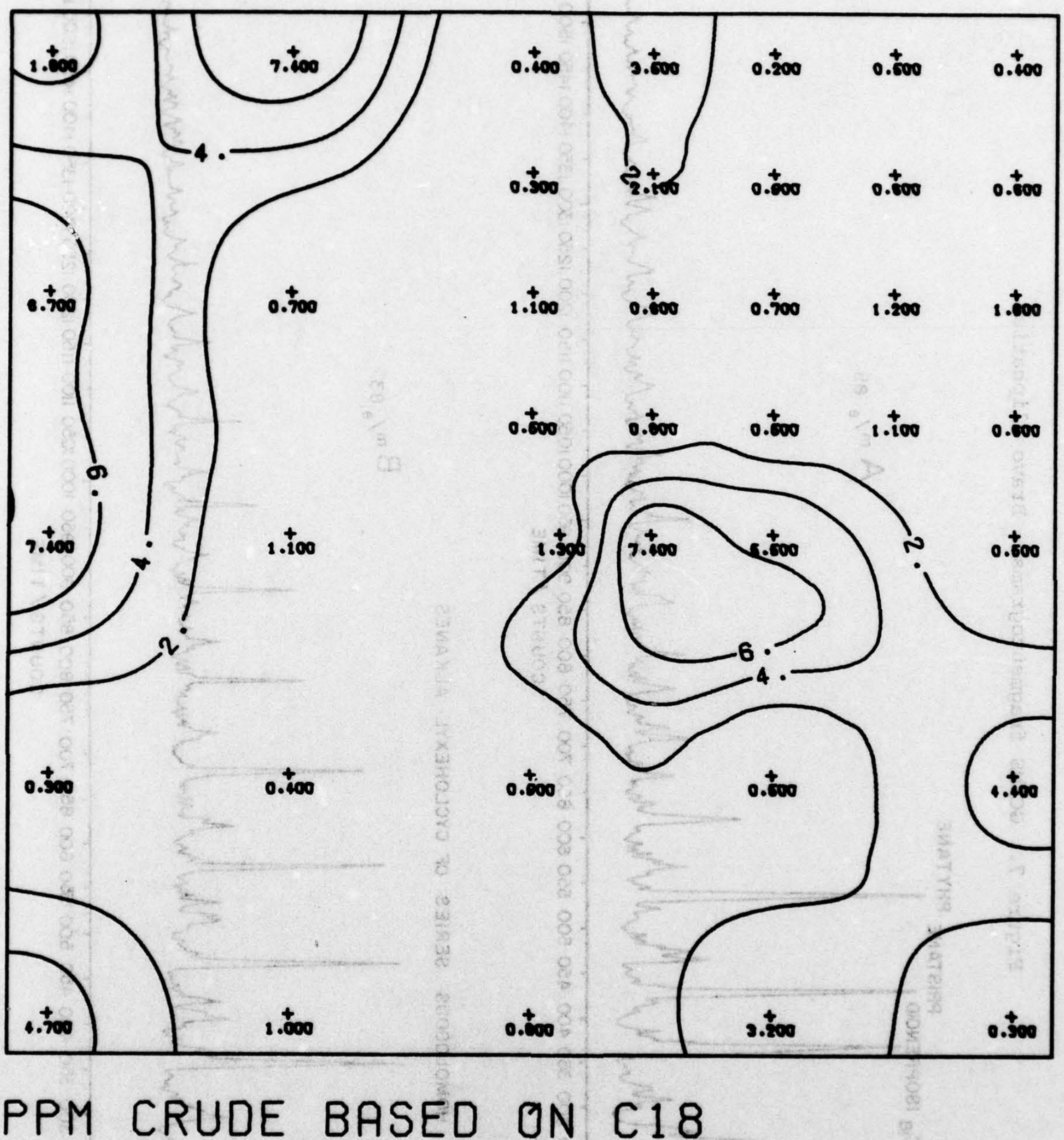


Figure 6.

Figure 7. GC/MS fragmentograms - Bravo aliphatics.

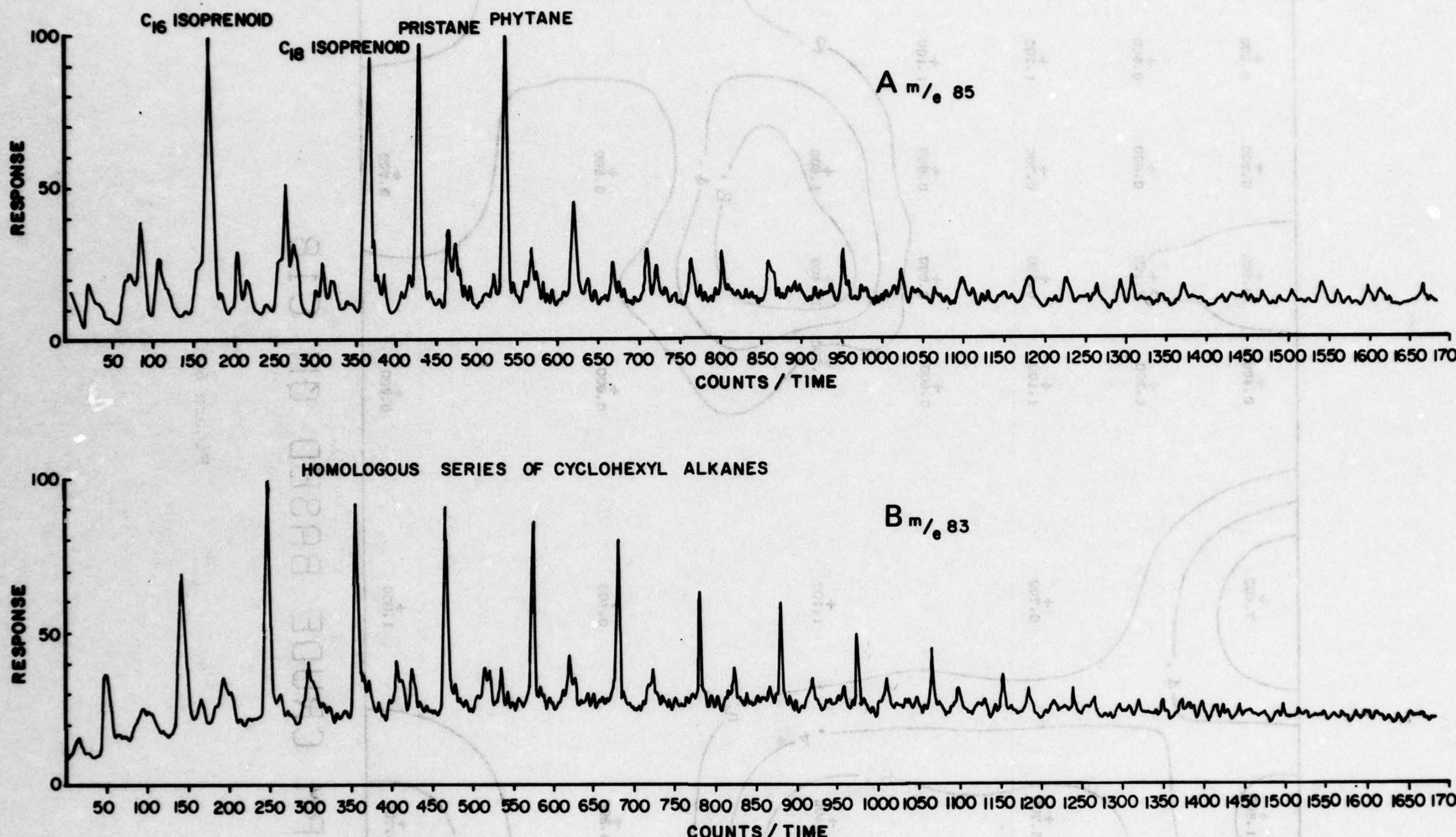
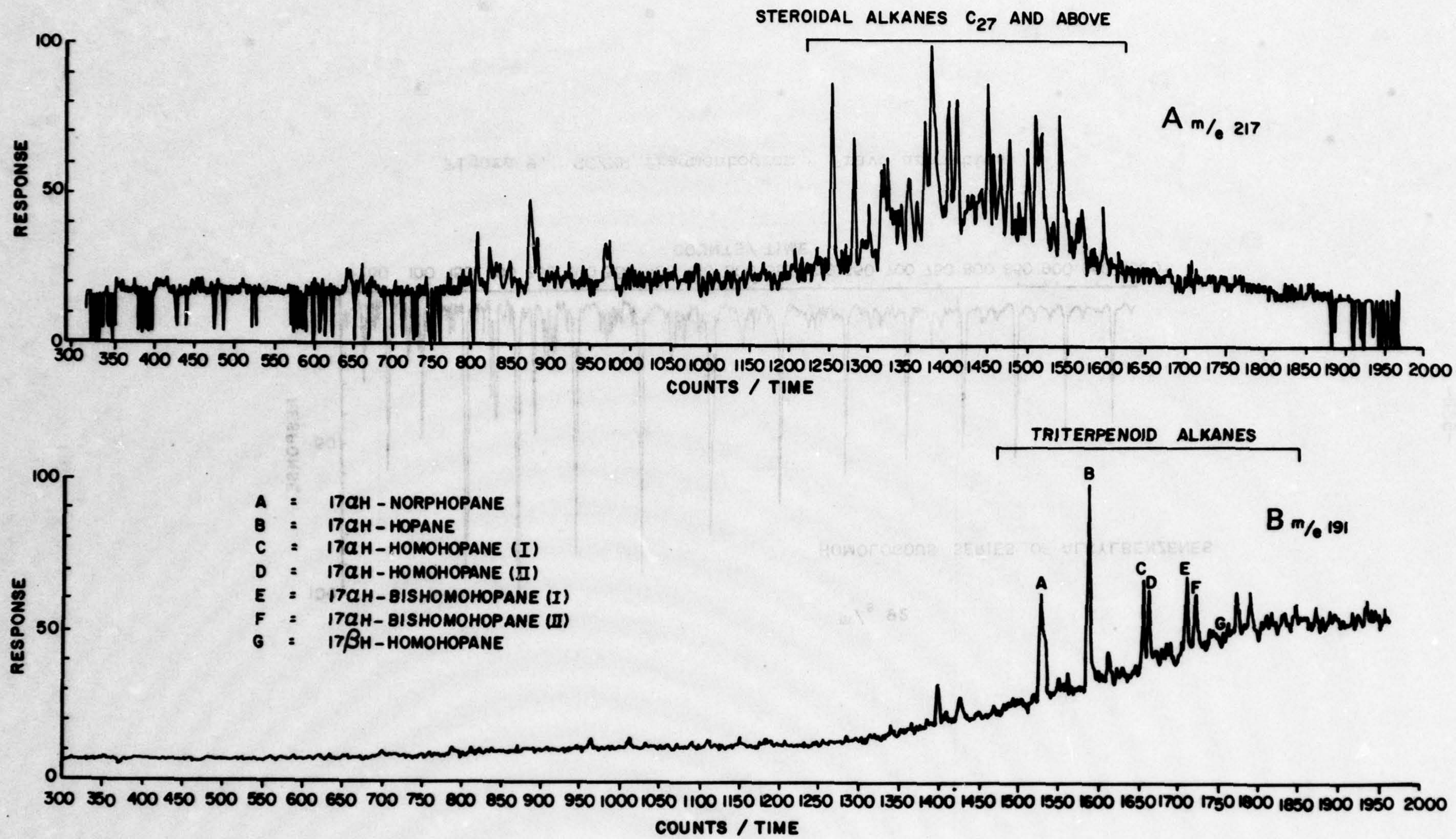


Figure 8. GC/MS fragmentograms - Bravo aliphatics.



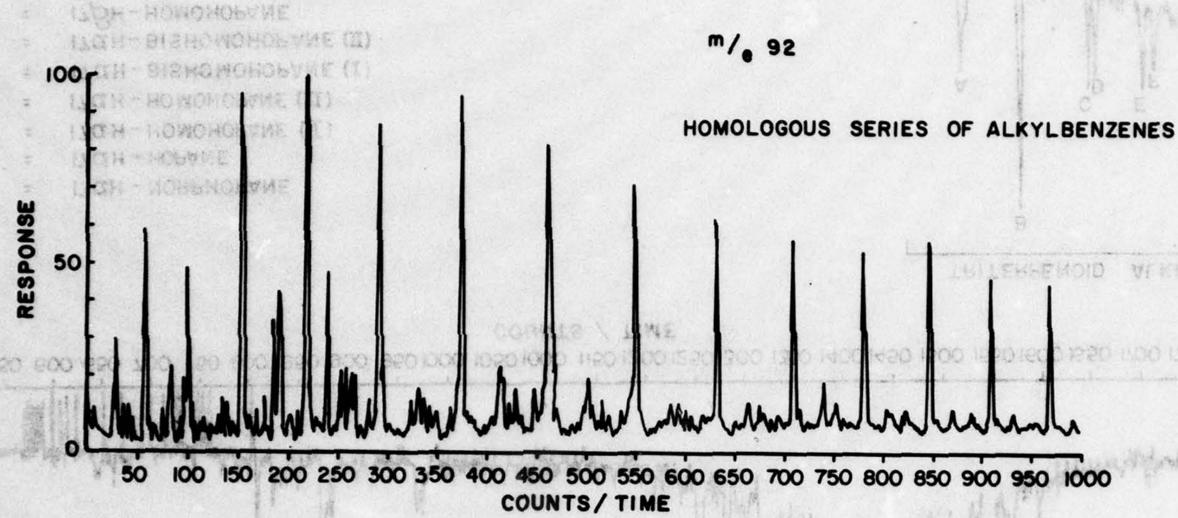
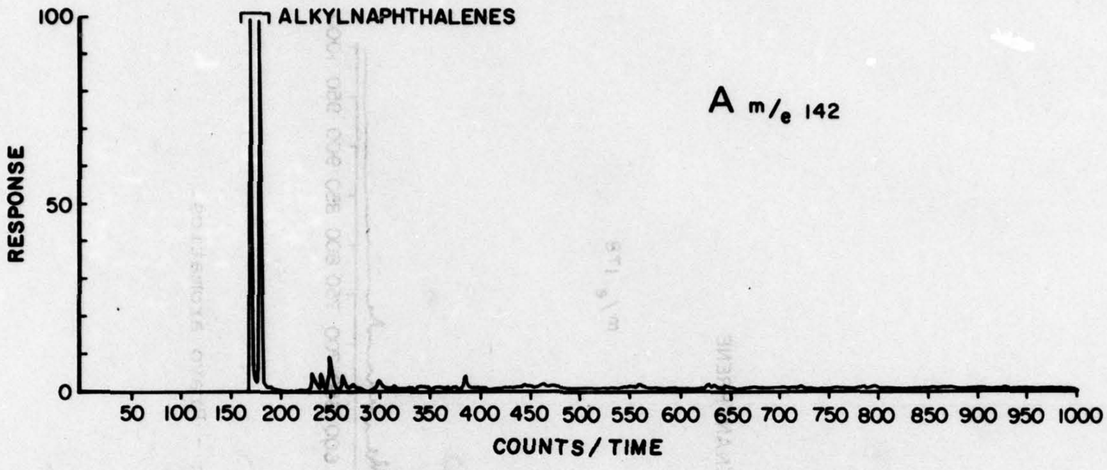


Figure 9. GC/MS fragmentogram - Bravo aromatics.



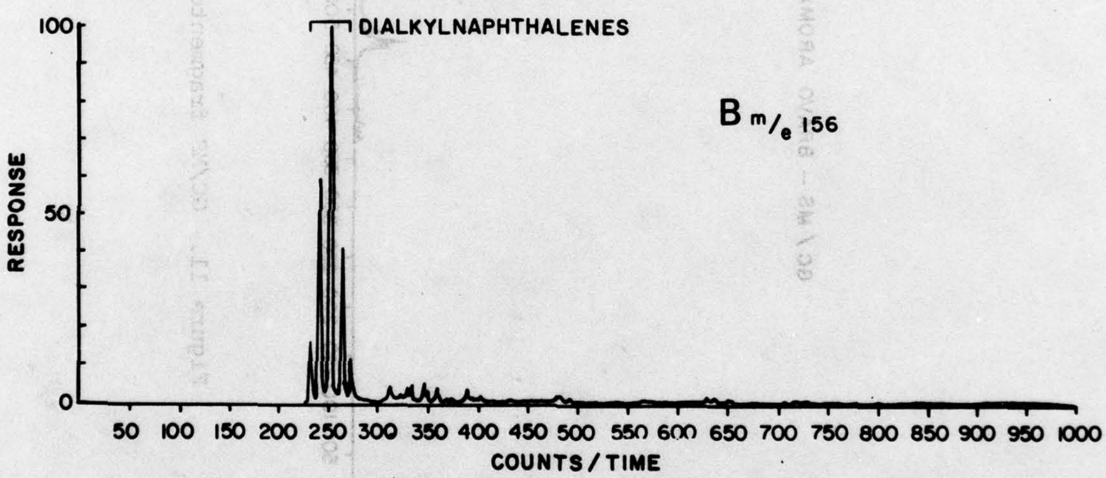


Figure 10. GC/MS fragmentograms - Bravo aromatics.

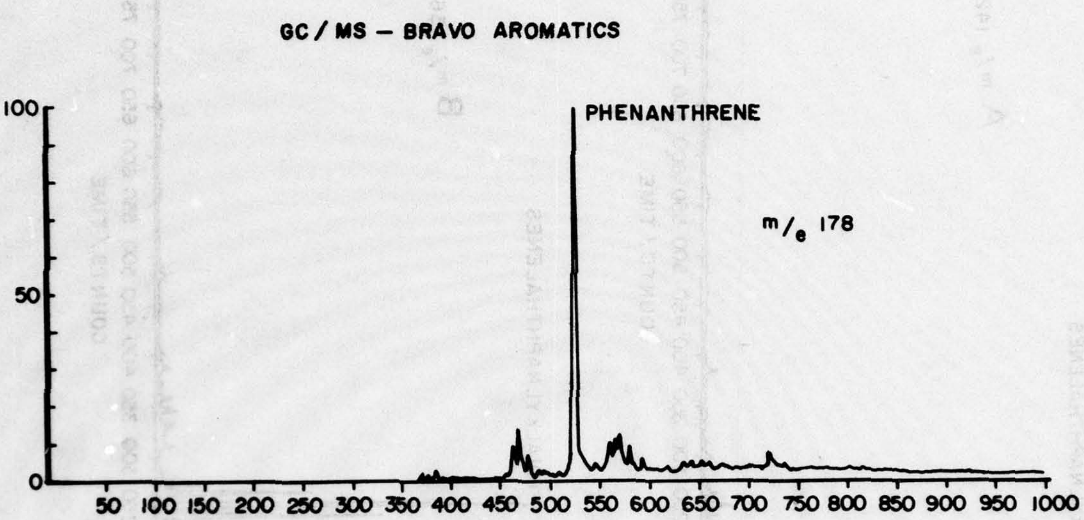


Figure 11. GC/MS fragmentogram - Bravo aromatics.

Table 1. Organisms subjected to analysis.

Organism Type	Sampling Location
Mussel	13, 57, 93
Clam	28, 29, 39, 75, 77, 93
Urchin	17, 28, 35, 36, 37, 45, 46, 56, 57, 77, 99

Table 2.

ALKYL FRACTIONS GC/MS SUMMARY

Sample Type	Location	m/e 85 Acyclic Alkane Series: Low Molecular Weight Range	m/e 85 Acyclic Alkane Series: High Molecular Weight Range	m/e 83 Cyctic Alkane Series	m/e 217 Stearane Series	m/e 191 C/D Ratio	m/e 191 C/G Ratio
Sediment	11		H[a]			0.60	2.0
	13	H, CPI[b]		S[c], "hump" present	S	0.50	2.2
	16	M[d], CPI		S		0.71	4.0
	26	M, CPI	H, CPI	S		0.80	>10
	28	H	H, CPI		G[e]	0.73	>10
	31	H, CPI	H			0.56	1.8
	35	M, CPI	H			0.67	2.9
	38	M	H			0.60	>10
	39	M	H			0.63	2.2
	48	M	M		G	0.95	>10
	51	M, CPI	H		S	0.56	2.3
	53	M	H		S	0.73	3.2
	TOR	M	H		S	0.86	6.3
	56	H, CPI	H	minor "hump"	S	0.68	3.1
	57	M	H	"hump" present	G	0.85	3.7
	59	M, CPI	H			0.61	2.2
	79	H, CPI	H		G	0.74	3.3
	93	M, CPI	H			0.65	3.1
	97	H, CPI	M			0.70	>10
Mussel	13	M, CPI	H, CPI			NM[f]	NM
	57	M	H, CPI		S	1.3	>10
	93	H	H, CPI			NM	NM
Clam	29	M	H, CPI	S	S	1.1	>10
	39	M	M, CPI			0.8	>10
	75	M	M			NM	NM
	77	M	M, CPI			NM	NM
	93	H, CPI	H, CPI			NM	NM
Bravo crude		H, CPI	H, CPI			1.2	>>10

[a] H - Indicates high relative abundance of lower molecular weight "alkyl" hydrocarbons.
[b] CPI - Indicates low carbon preference index.
[c] S - Indicates some similarity to Bravo crude.
[d] M - Indicates minor abundance.
[e] G - Indicates good comparison with Bravo crude.
[f] NM - Negligible peak intensities preclude measurement.

Table 3.

AROMATIC FRACTIONS
GC/MS SUMMARY

Sample Type	Location	Alkylbenzene Series m/e 92	Alkyl-naphthalenes m/e 142	Dialkyl-naphthalenes m/e 156	Phenanthrene (ppt) m/e 178
Sediment	11 spiked	H[a]	H,G[b]	H,G	68
	11				35
	13	L[c]			16
	16			M	28
	26				9
	28				5
	31				9
	35	H	S[d]	S	38
	38	H	S	S	31
	39	H	S	S	<5
	48		S	S	13
	51				140
	53	L			125
	TOR	L		S	140
	56				7
	57	L	S	S	68
	59				35
	79	L		S	33
	93	H		S	158
	97				148
Mussel	13				<5
	57				<5
	93				<5
Clam	29				<5
	75				<5
Bravo					10^6

[a]H - Indicates high relative abundance of components characteristic of Bravo crude.
[b]G - Indicates good comparison with Bravo crude.
[c]L - Indicates low relative abundance of components attributable to Bravo crude.
[d]S - Indicates some similarity to Bravo crude.

Table 4.

CRUDE OIL INPUT

ALKYL	Long Term			Sediments:	33 of 41 locations
				Organisms:	6 of 22 individuals
	Recent			Sediments:	12 locations
				Organisms:	4 individuals
		Stearanes	Good match with Bravo	Sediments:	26,28,48,TOR,57
				Organisms:	Mussel 57, Clam 29
			Similar to Bravo	Sediments:	13,15,16,79,93
		Triterpanes	Good match with Bravo	Sediments:	26,28,48,TOR.57
				Organisms:	Mussel 57, Clam 29,39
			Similar to Bravo	Sediments:	11,13,16,77,91
AROMATIC	Long Term			Sediments -	14 locations
	Recent			Sediments -	26,28,TOR,57, 1

BIOLOGICAL MONITORING OF SEDIMENTS IN EKOFISK OILFIELD

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ABSTRACT

A biological monitoring scheme for the Ekofisk oilfield was initiated in 1973, based on intensive quantitative sampling of the benthic macrofaunal community close to the installations.

Samples were taken with a 0.1 m^2 grab and the biological material was screened with a 1 mm mesh. Sediment particle size analysis was carried out in all surveys, and hydrocarbon analysis of sediments from 26 stations was carried out in 1977.

It is suggested that the observed changes in community structure are due to industrial activity in the area. Oil pollution and other factors such as mechanical disturbance and domestic waste are considered.

An evaluation of this monitoring programme is presented. It is concluded that the methods used are adequate to detect and measure the spatial extent of changes which have occurred in the benthic macrofauna.

INTRODUCTION

A biological monitoring scheme for the Ekofisk oilfield was initiated in August 1973. This involved intensive quantitative sampling of the benthic macrofaunal community. Sampling was repeated in August 1975 and August 1977 using the same methods and, where possible, the same sampling stations.

This paper will concentrate in detail on the results of the August 1977 survey, using earlier work carried out by B. Dicks to give some historical perspective.

The objectives of this work were:

1. to provide a description of the macrobenthic fauna of the area in terms of species composition and abundance;
2. to provide data from successive surveys suitable for use in the detection and monitoring of changes which may occur in the community.

Although possible effects of ballast water discharged from the central storage tank were the prime concern, the sampling stations were spaced widely enough to include all the installations.

METHODS

(i) Sampling methods.

Wherever possible the sampling stations visited have been the same in all three surveys. These 24 stations are arranged on a series of five radiating lines centred on the storage tank. (See Figs. 1 and 2 for location of sample stations.) A further three stations were established in 1977 around B platform. The total area covered by these surveys is approximately 120 km^2, the most remote stations being approximately 6 km from the central storage and production complex.

Position fixing was achieved using lines of sight on fixed installations in conjunction with radar ranges and bearings. In view of the large number of fixed structures in the area and the relative proximity of sampling stations, considerable accuracy can be achieved using these methods. Wherever possible, sampling was carried out with the boat at anchor, though at sites where anchoring was prohibited the engines were used to maintain position.

The sampling procedures have been described by Dicks (1975). A Day grab was used to obtain replicate 0.1 m^2 samples from each station. Depth of penetration was approximately 10 cm at all stations sampled. After retrieval of the sample, the contents of the grab were sieved using a 1 mm mesh and a seawater hose. All material retained on the sieve was preserved in alcohol and stained with eosin to facilitate subsequent laboratory sorting.

In order to obtain an accurate estimate of species densities and rarer species occurrences, ten replicate biological samples were taken at most stations. At stations 25, 26 and 27 in 1977, three replicates were taken to give an estimate of the density of the more common species. A further sample was taken at each station to provide sediment for particle size analysis and hydrocarbon analysis.

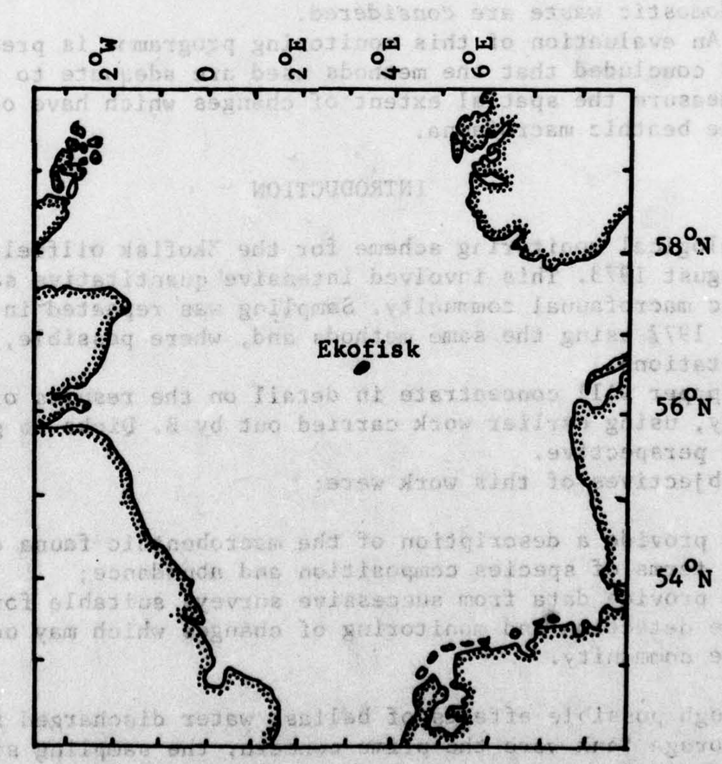

Fig.1. Location of Ekofisk oilfield.

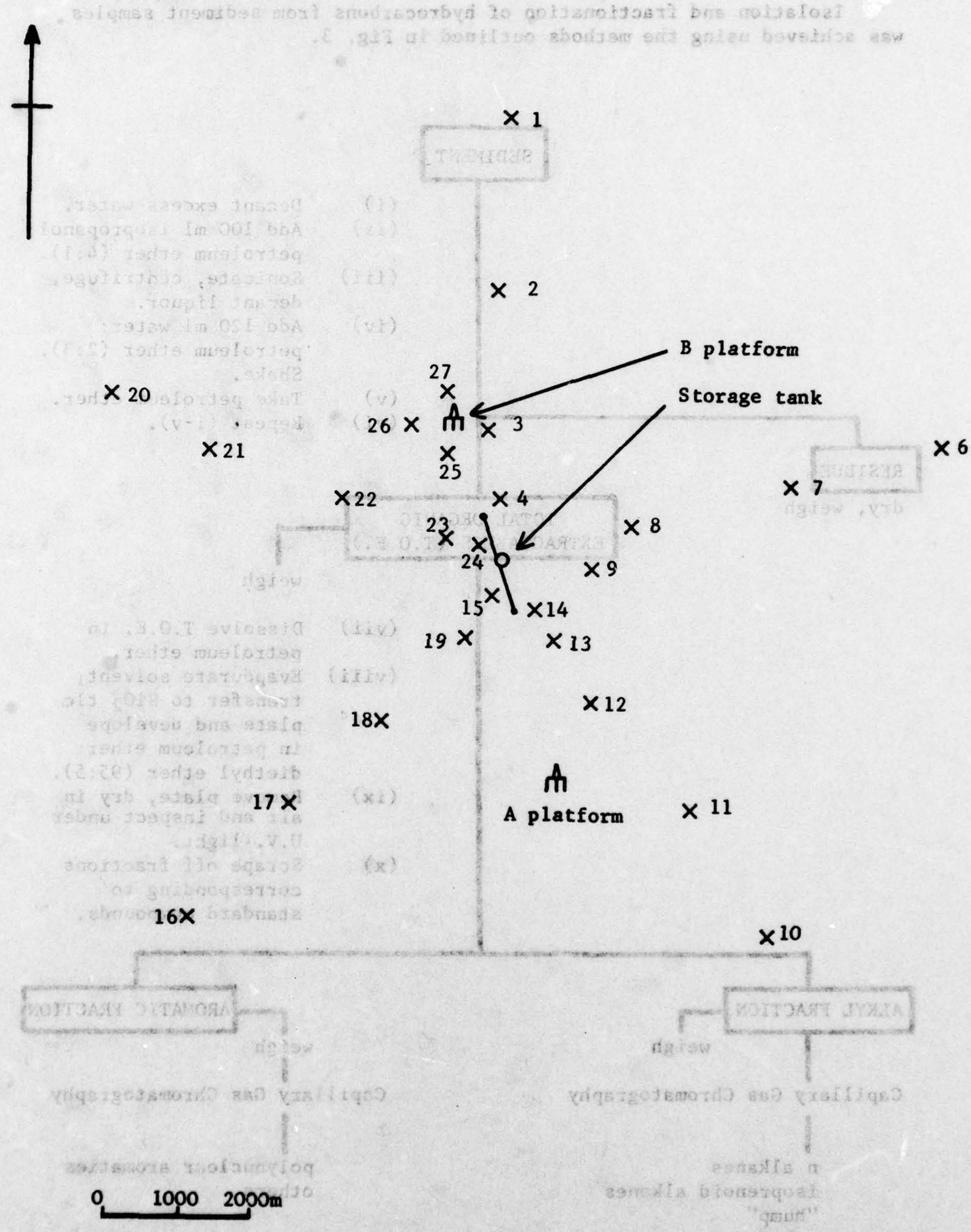

Fig. 2. Location and numbering of sample stations in relation to fixed installations.

(ii) Laboratory Procedures and Data Analysis.

Hydrocarbon analysis of sediment samples. This work was carried out by Masspec Analytical (Specialty Services) Ltd. to provide a semi-quantitative assessment of hydrocarbon levels in the sediment for comparison with the biological data.

Isolation and fractionation of hydrocarbons from sediment samples was achieved using the methods outlined in Fig. 3.

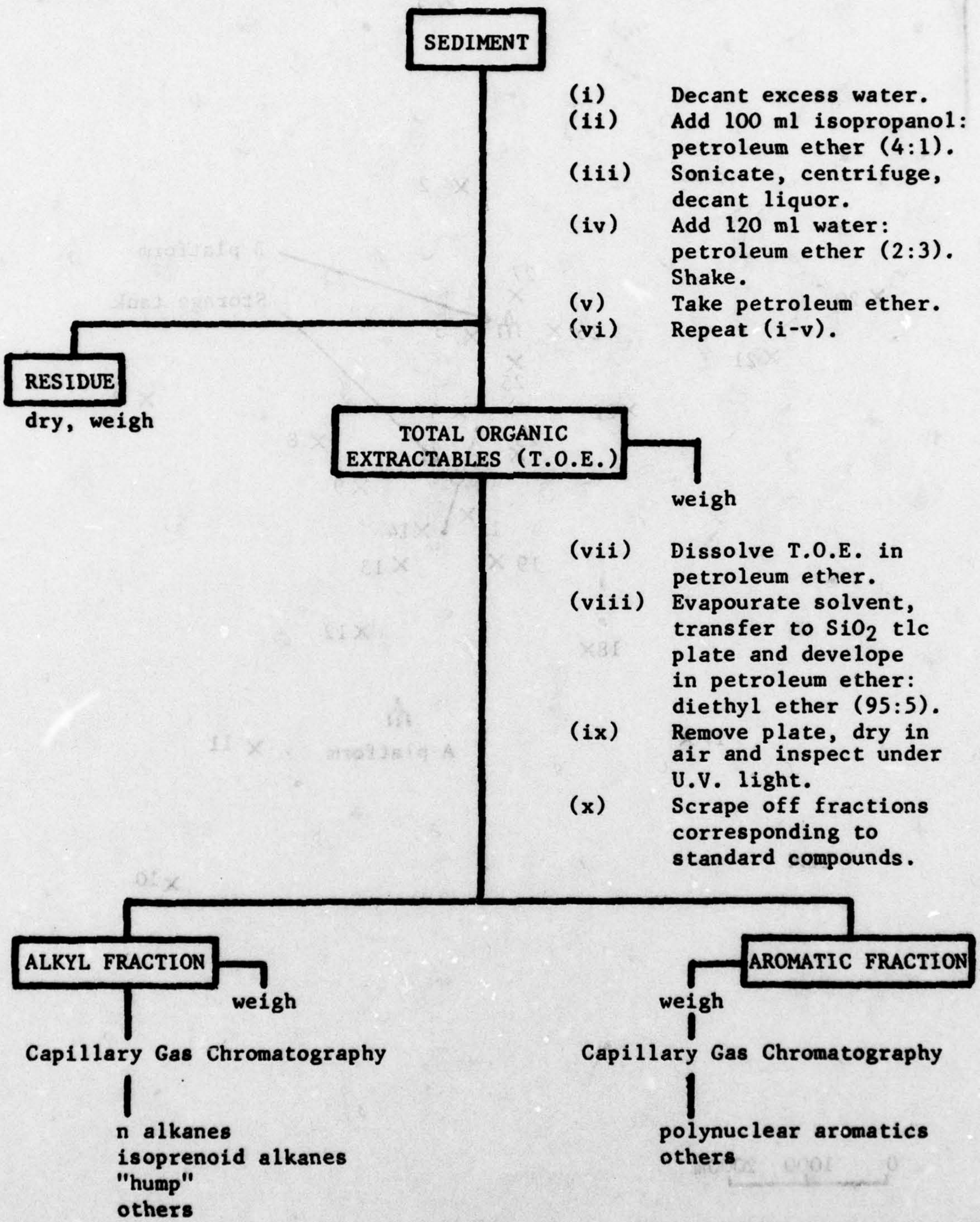

Fig. 3. Outline of procedures used in hydrocarbon analysis of sediment samples.

Aliquots of both the "alkyl" and "aromatic" fractions from 25 sediment samples were analysed by capillary gas liquid chromatography under the following conditions: Instrument: Finnigan 9500. Column: 20 m x 0.2 mm OV-101. Programmed from 60-260°C at 6°/min. He flowrate 2-3 ml/min.

Biological samples. In the laboratory, all stained material was examined and the animals picked out. Identification was made to species level where possible, though a number of groups and indeterminate species are also present in the data.

A total of 122 taxa (i.e. species or groups of species) were isolated from the samples in 1977. The number of individuals in each taxa was recorded for each grab sample, and the data is summarised for each station in the Appendix as densities of each taxa in numbers per m^2.

Confidence limits were calculated for total population density at each station.

The Shannon-Weiner information function H(S) was calculated for each station. This diversity index is given with number of species and total number of individuals for each station in Table 1.

The densities of a number of groups and species at each station are illustrated in Figs. 4 to 13. In these figures the area of each circle is proportional to the density.

Sediment particle size analysis. The methods used to separate and determine the silt content of the sediment involved the wet-sieving technique outlined by Buchanan (1971). After initial splitting, the coarser material was fractionated by dry sieving, and the weight of each fraction was expressed as a dry weight percentage.

Cumulative weight percentages were plotted against particle size in microns on semi-logarithmic graph paper. A number of sediment parameters were then calculated for each sample and these are presented in Table 2.

The percentage of material passing through a 64 μ sieve is a useful estimate of the amount of silt present in the samples and is expressed as percentage fines (% fines).

The Phi Quartile Deviation (QDØ) describes the slope of the curve between the first and third quartiles. Perfect sorting would be represented by a vertical curve, so a lower value of QDØ indicates a better sorted sediment.

Phi Quartile Skewness (SkqØ) indicates how much the curve is skewed between the quartiles. A straight line would give SkqØ = 0. A positive sign indicates that the particles larger than the median are better sorted than the smaller, and a negative sign that the smaller are better sorted.

RESULTS OF AUGUST 1977 SURVEY

Biological Samples.

It was found in 1977 that sample stations close to the central storage and production complex and those close to B platform have a reduced total density of individuals per m^2 (see Fig. 4). A similar variation in the number of species found at each station is also apparent (Fig. 5). These two parameters give an overall indication of industry-related changes in macrobenthic community structure.

A more detailed analysis has been carried out by looking separately at the distributions of the main species present in the survey area.

The numerically dominant species at most stations is the polychaete Myriochele oculata. This species achieves its maximum density of 2840 per m^2 at station 20. Fig. 6 shows a marked reduction in density of M. oculata at stations close to the central complex and B platform. A density gradient away from these installations is also suggested by the distribution of this species.

The organism which achieves the second highest maximum density in the 1977 survey is another polychaete, Chaetozone setosa. This species has a distribution pattern quite the reverse of Myriochele oculata, achieving its maximum density at station 25 close to B platform (see Fig. 7).

The distributions of other numerically top-ranked species are shown in Figs. 8 to 12. Owenia fusiformis (Fig. 8) follows the pattern of the closely related species, Myriochele oculata. Amphiura filiformis (Fig. 9) also shows a density gradient, increasing with distance from the installations.

A number of other numerically high-ranking species do not exhibit a clear density gradient. For instance, Goniada maculata (Fig. 10) has only a slight reduction in density at the inner stations. Pholoe minuta (Fig. 11) has a particularly patchy distribution. The bivalve Arctica islandica, which is mostly represented by juveniles, achieves high densities close to B platform and at station 15 close to the storage tank (Fig. 12).

From these distribution maps it is apparent that the reduction in total numbers of individuals is largely accounted for by the reduced densities of Myriochele oculata at inner stations. This overall reduction is offset to an extent by the increase in numbers of Chaetozone setosa at some inner stations. Fig. 13 shows the density of individuals per m^2 less C. setosa. This distribution closely follows that of Myriochele oculata, Owenia fusiformis and Amphiura filiformis.

The presence of a density gradient is suggested by the distribution maps. This is further supported by Figs. 14 to 16, which show regression lines calculated for total population density, number of species and density of Myriochele oculata plotted against distance from either the central storage tank or B platform. In each case there is a continuous increase in density away from the installations.

Possible explanations for the observed density gradients are discussed later. The biological data suggests that the agents responsible for changes in community structure are likely to show similar gradients.

It has been mentioned that there is also a reduction in the number of species found at the inner stations. To determine which types of organisms account for this reduction, the total number of species at each station was split into the main groups. This analysis showed that polychaete species account for most of the reduction in numbers of species encountered. Stations 25, 26 and 27 were not included in this analysis for reasons mentioned below.

The Shannon-Weiner function, H(S), calculated for each station except 25, 26 and 27, is shown in Table 1 together with total number of individuals per m^2 (N) and number of species (S). Stations 25, 26 and 27 were not included in diversity estimates because the reduced number of replicates at these stations results in a reduction of rare species encountered. From Fig. 17 it is clear that there is an increase in diversity close to the installations. This is largely due to the decreased numerical dominance of Myriochele oculata at these stations. It should be pointed out that the values of H(S) must be regarded as relative rather than absolute measurements of diversity due to the presence of grouped taxa in the data.

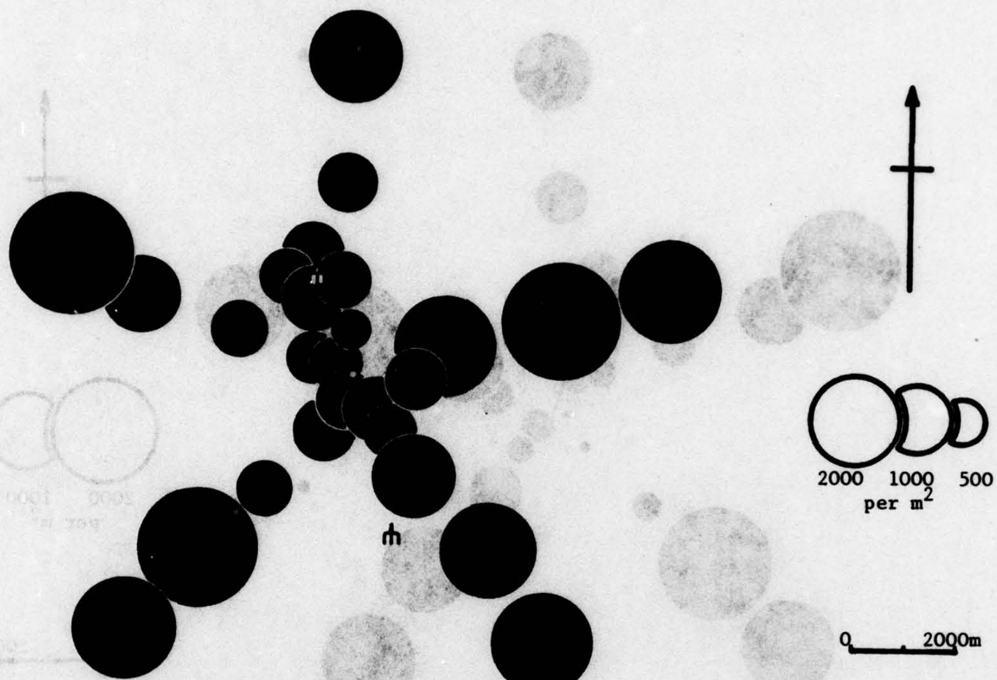

Fig. 4. Total population density at each station.

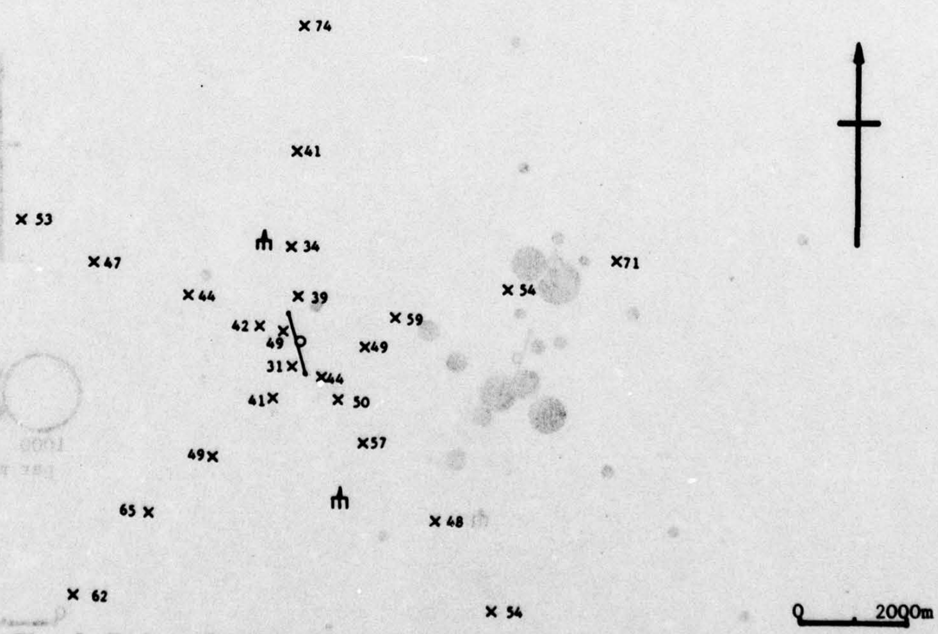

Fig. 5. Number of species at each station.

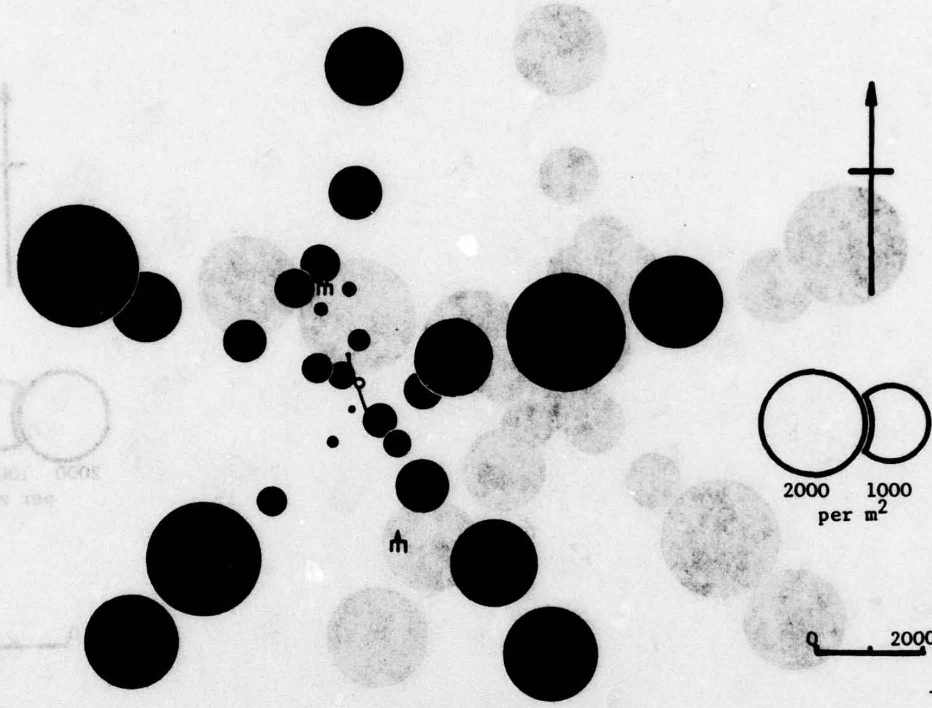

Fig. 6. Density of Myriochele oculata at each station.

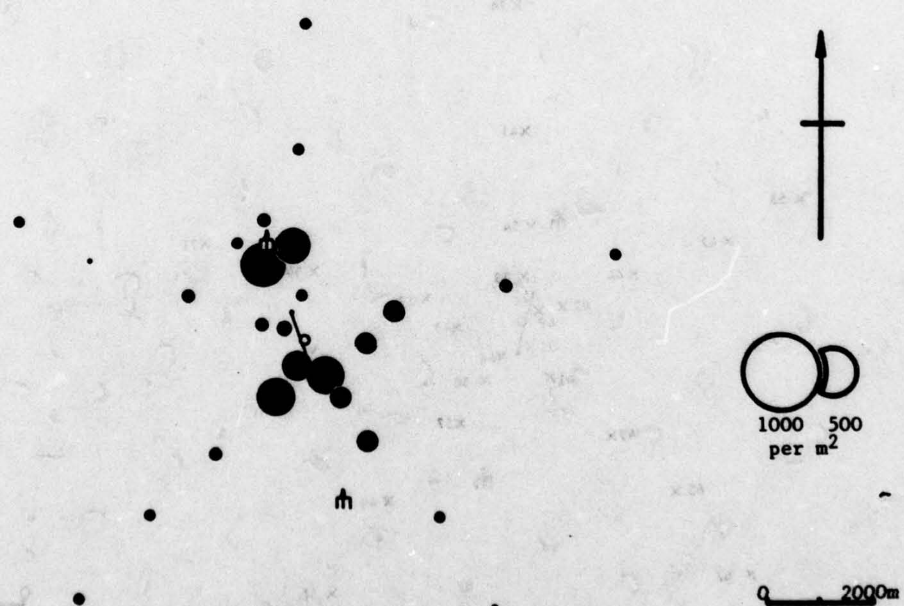

Fig. 7. Density of Chaetozone setosa at each station.

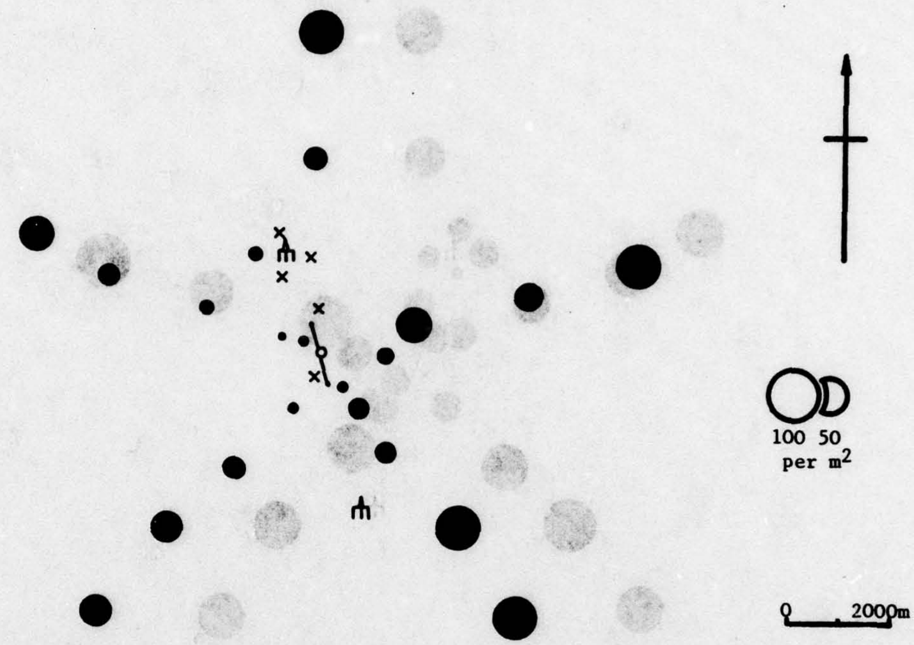

Fig. 8. Density of <u>Owenia fusiformis</u> at each station.

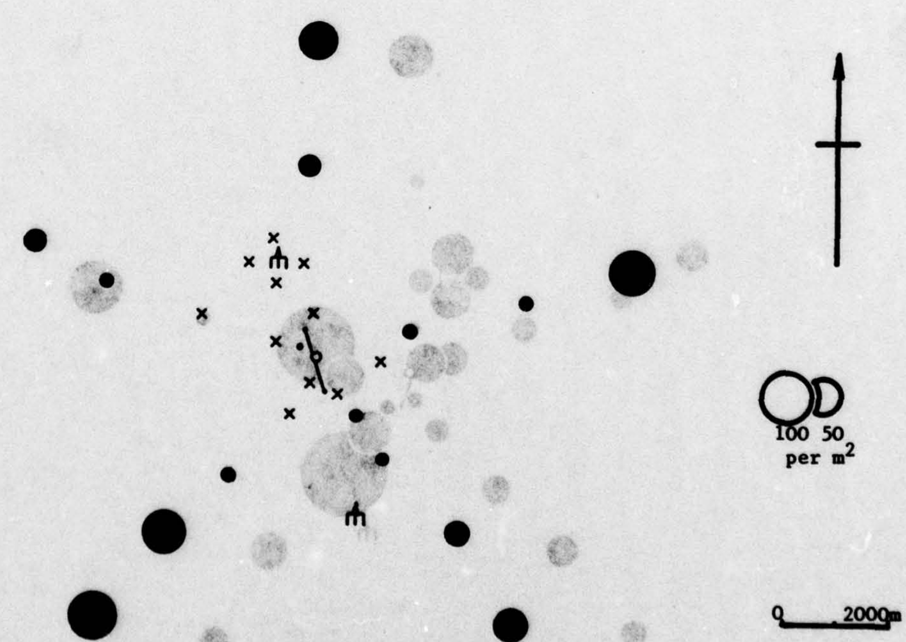

Fig. 9. Density of <u>Amphiura filiformis</u> at each station.

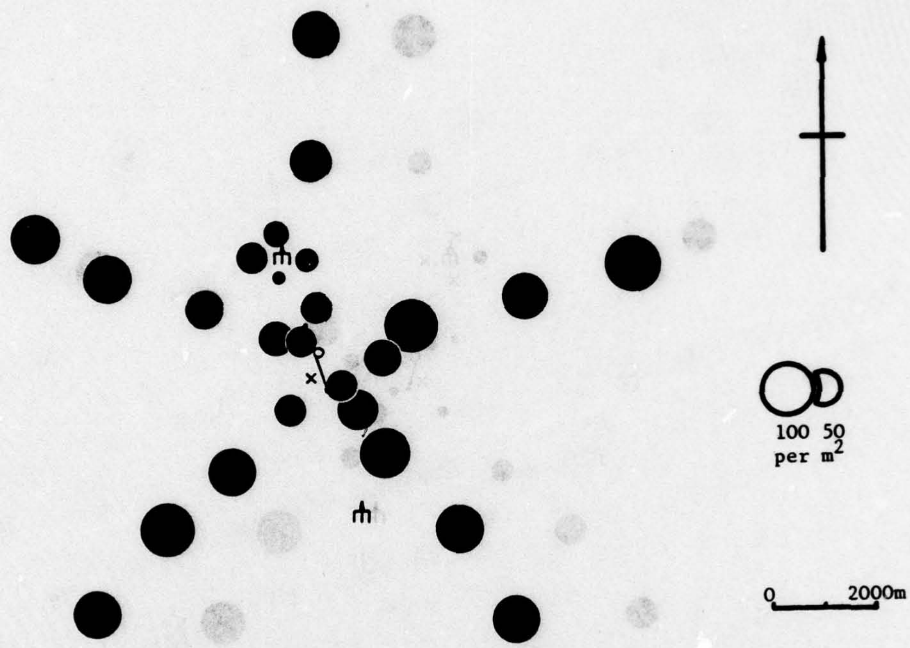

Fig. 10. Density of Goniada maculata at each station.

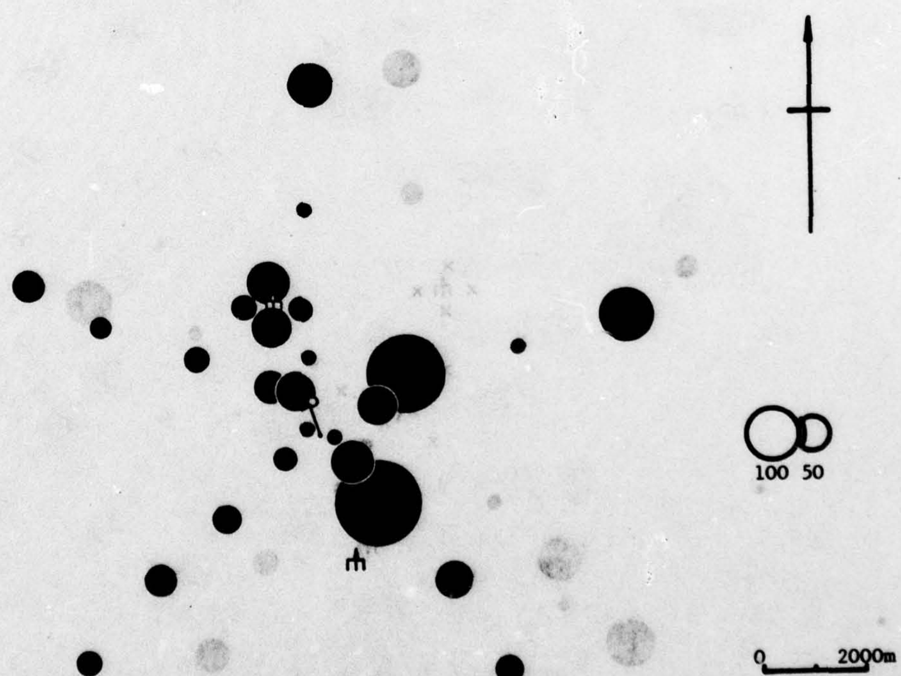

Fig. 11. Density of Pholoe minuta at each station.

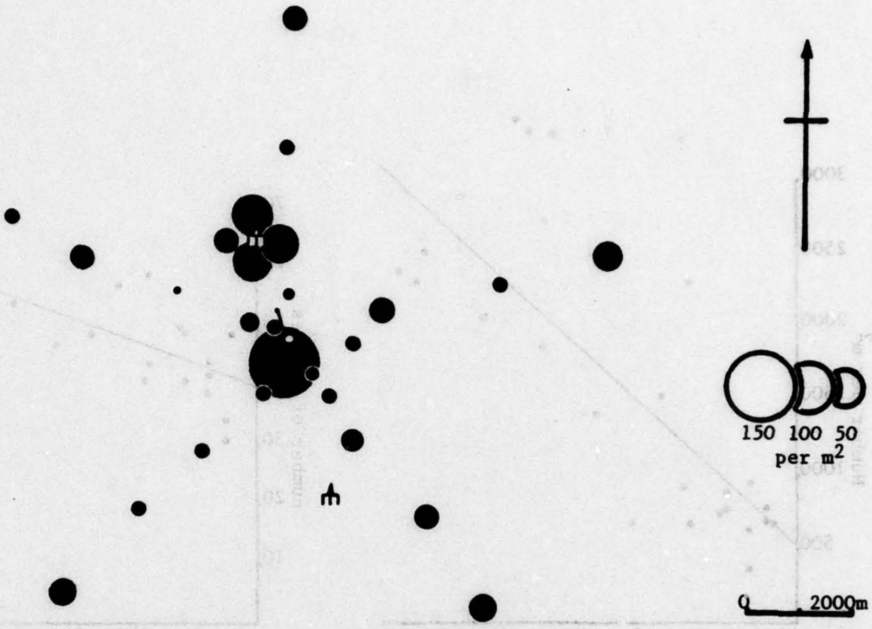

Fig. 12. Density of Arctica islandica at each station.

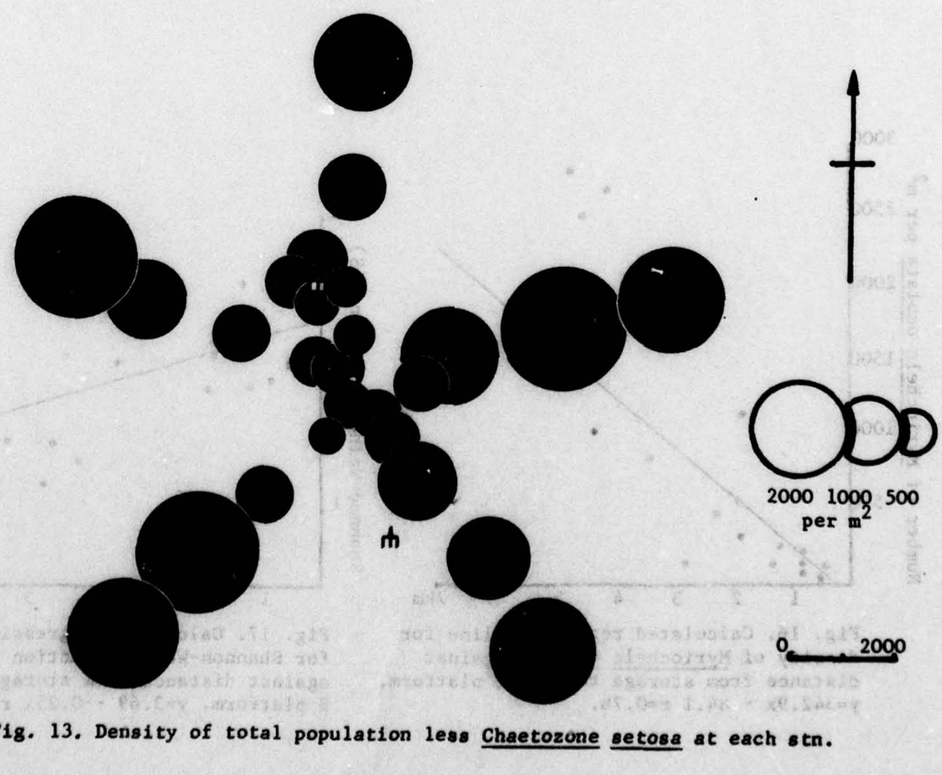

Fig. 13. Density of total population less Chaetozone setosa at each stn.

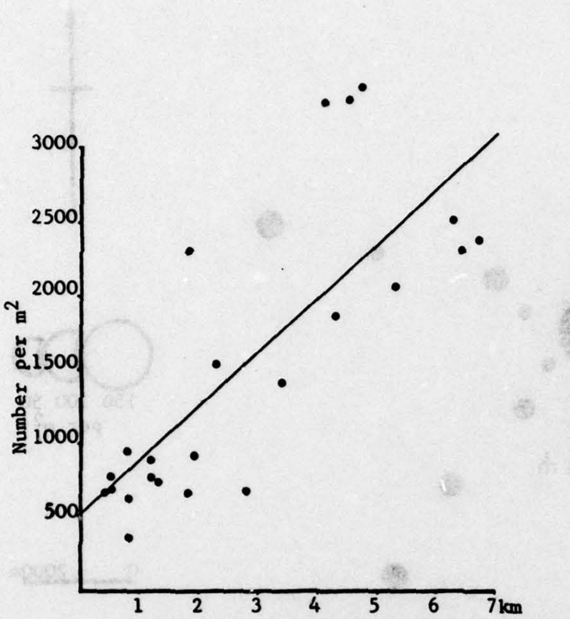

Fig. 14. Calculated regression line for total population density against distance from storage tank or B platform. y=370.76x + 508.4 r=0.78.

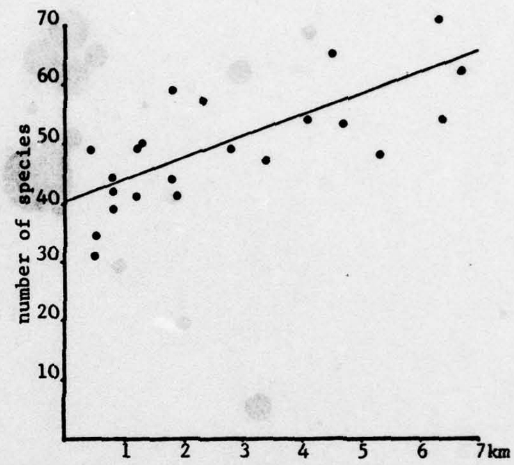

Fig. 15. Calculated regression line for number of species against distance from storage tank or B platform. y=3.65x = 40.2 r=0.7.

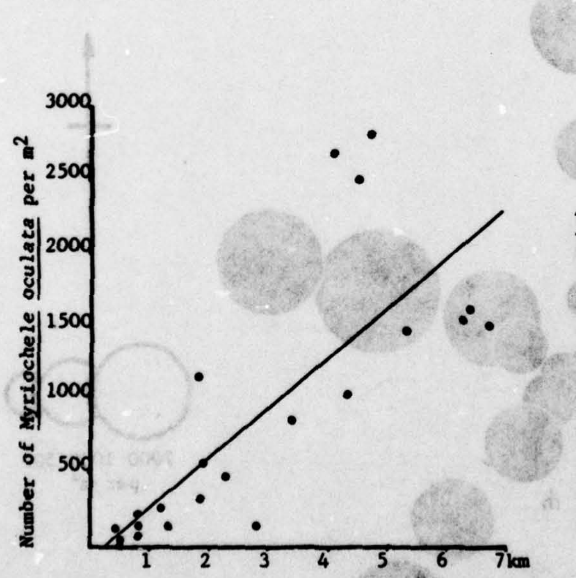

Fig. 16. Calculated regression line for density of Myriochele oculata against distance from storage tank or B platform. y=342.9x - 84.1 r=0.78.

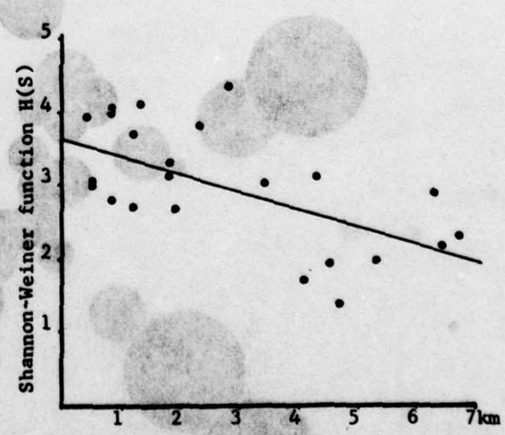

Fig. 17. Calculated regression line for Shannon-Weiner function (H(S)) against distance from storage tank or B platform. y=3.69 - 0.25x r=0.62.

Table 1. Shannon-Weiner function H(S), number of species S and total number of individuals per m^2 (N) at each station. 95% confidence limits are given for N.

Station	H(S)	S	N	Confidence limits
1	3.14	74	1874	±319
2	2.68	41	913	±248
3	3.02	34	696	±257
4	4.05	39	359	± 84
6	2.90	71	2532	±280
7	1.68	54	3326	±483
8	3.14	59	2339	±271
9	3.66	49	896	±352
10	2.19	54	2325	±485
11	1.98	48	2076	±342
12	3.80	57	1543	±129
13	4.10	50	730	±153
14	2.81	44	956	±236
15	3.01	31	774	±219
16	2.34	62	2390	±306
17	1.90	65	3356	±291
18	4.35	49	681	±744
19	2.71	41	771	±216
20	1.39	53	3434	±799
21	3.01	47	1417	±428
22	3.32	44	688	±247
23	3.98	42	601	±236
24	3.93	49	670	±243

Sediment Particle Size Analysis.

The sediments in the survey area are characterised by fine sand (Wentworth grade). The mean median particle diameter of 26 samples taken from approximately 140 km^2 is 136.3 ± 1.98 μm (confidence limits at 0.05 probability level). This indicates a considerable spatial uniformity, which is also reflected in the sorting of the sediment. The mean quartile deviation is 0.32 which describes a well sorted deposit. The mean phi quartile skewness is only 0.0035 which indicates that sorting on each side of the median is of the same order, or only very slightly more efficient among the larger diameters (see Table 2).

Due to their peaked nature the distributions have very minor "tails". At the coarse end, they consist of coarse and medium sand grade shell fragments, totalling only 4.3% in the coarsest sample. The proportion of fines in the samples varies from 2.48% to 7.72%. The higher proportions are found near the installations but because the increase involved is slight, it is difficult to assess its significance without more detailed physical analysis of the sediments throughout the area. The increase may possibly be related to physical disturbance of the seabed around the installations.

Table 2. Sediment particle size analysis data.

Station	Median particle diameter μm	Corresponding Wentworth grade	Phi qurtile deviation	Phi quartile skewness	% fines
1	137	Fine sand			3.10
2	142	"			3.47
3	141	"			5.04
4	137	"			7.72
6	138	"	0.32	0.01	3.12
7	139	"	0.31	0.02	2.48
8	130	"	0.35	-0.01	3.62
9	137	"			3.88
10	151	"			3.48
11	135	"	0.32	0.01	3.20
12	133	"	0.37	-0.03	4.10
13	133	"	0.34	0.01	5.46
14	130	"	0.35	0.00	3.72
15	130	"	0.32	0.00	6.54
16	144	"	0.28	0.02	3.57
17	142	"	0.31	0.01	4.44
18	138	"	0.32	0.00	4.48
19	132	"	0.32	0.01	4.02
20	136	"	0.31	0.04	3.88
21	137	"	0.30	0.01	4.53
22	133	"	0.31	-0.02	4.42
23	137	"	0.32	0.01	4.76
24	133	"	0.31	-0.03	3.52
25	131	"	0.33	0.00	5.86
26	135	"	0.31	0.04	4.78
27	133	"	0.31	-0.03	4.88

Hydrocarbon Analysis of Sediments.

For the purposes of visual comparison with biological data, a number of parameters have been mapped in Figs. 18 to 22.

Fig. 18 shows "Total Organic Extractables" (T.O.E.) in μg/g dry weight of sediment at each station except station 1, for which no hydrocarbon analysis was performed due to loss of sample. Sediment samples from most stations close to the central complex and B platform have a relatively high T.O.E. content.

Possibly more useful gravimetric estimates are the concentrations of "alkyl" and "aromatic" compounds in the sediment (Figs. 19 and 20). The concentrations of alkyl compounds reaches a maximum at station 15 and is also high at three of the four stations close to B platform.

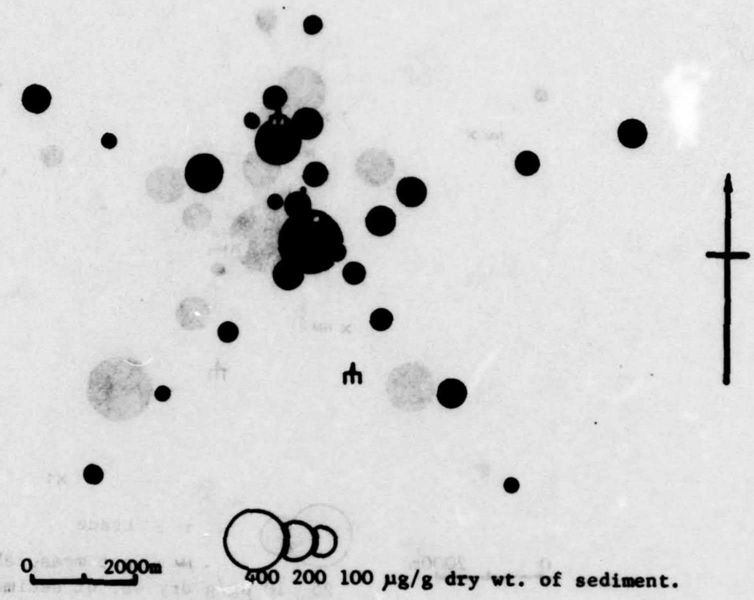

Fig. 18. Amount of "Total organic extractables" at each station.

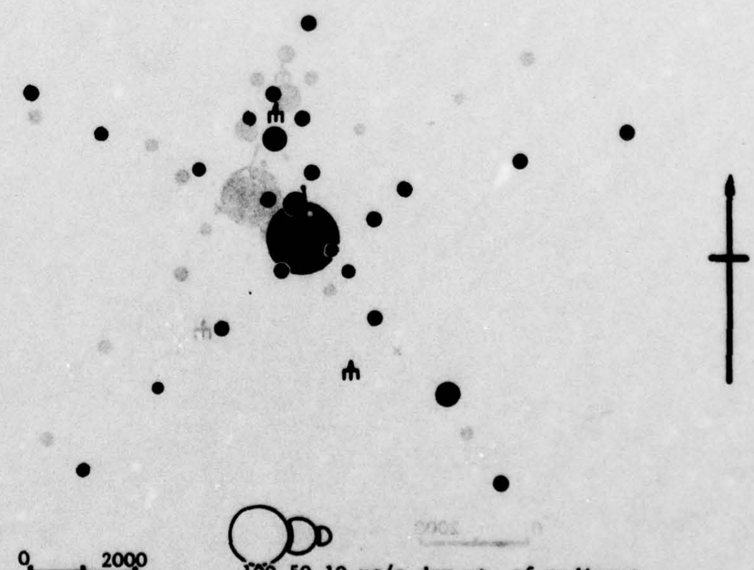

Fig. 19. Amount of "alkyl" compounds at each station.

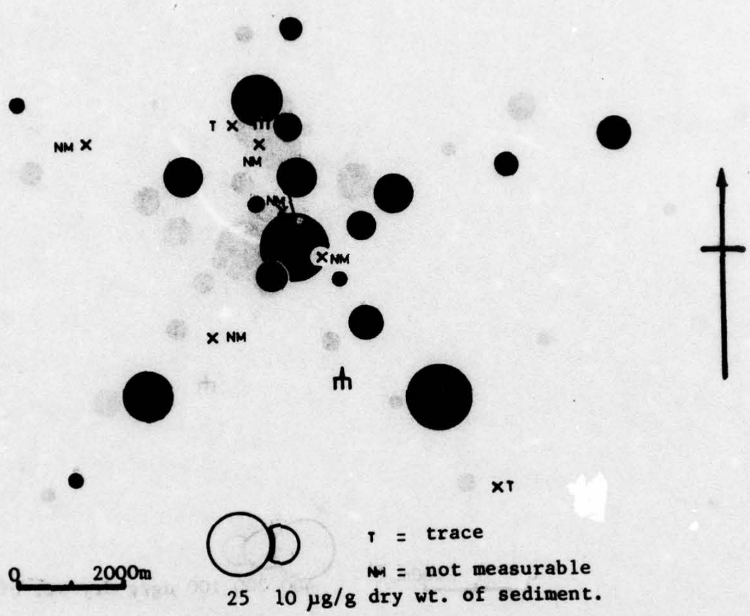

Fig. 20. Amount of "aromatic" compounds in sediment at each station.

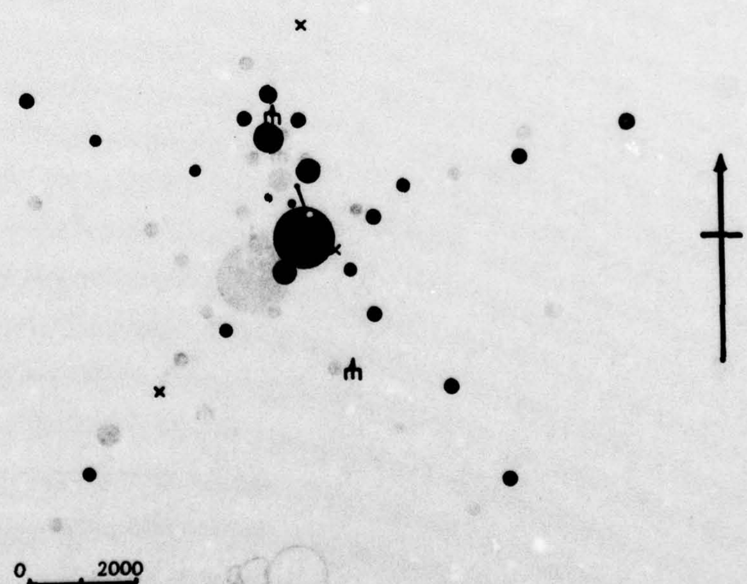

Fig. 21. "Relative hump area" per g dry wt. of sediment at each station.

The concentrations of aromatic compounds is high at the innermost stations and at stations 11 and 17. Such gravimetric estimates should be used with caution due to the possible presence of elemental sulphur and the variable amount of animal material in samples from different stations.

More reliable information can be obtained from gas chromatographic analysis of the samples. The size of the unresolved envelope or "hump" is used here as an indication of the relative amount of degraded hydrocarbons present in the sample. The "relative hump area per gram" for each sample is shown in Fig. 21 and tends to be highest at stations close to the installations.

The nC_{18}/nC_{29} ratio is used as an indication of the amount of undegraded crude oil in relation to naturally occurring (i.e. biological) hydrocarbons in the sediment at each station. Fig. 22 shows that this ratio is highest around B platform.

The difficulties associated with hydrocarbon analysis in the marine environment are well known. Caution dictates that the procedures used here should be regarded as semi-quantitative. The values obtained from the various analyses carried out have been treated as relative indications of hydrocarbon contamination throughout the survey area.

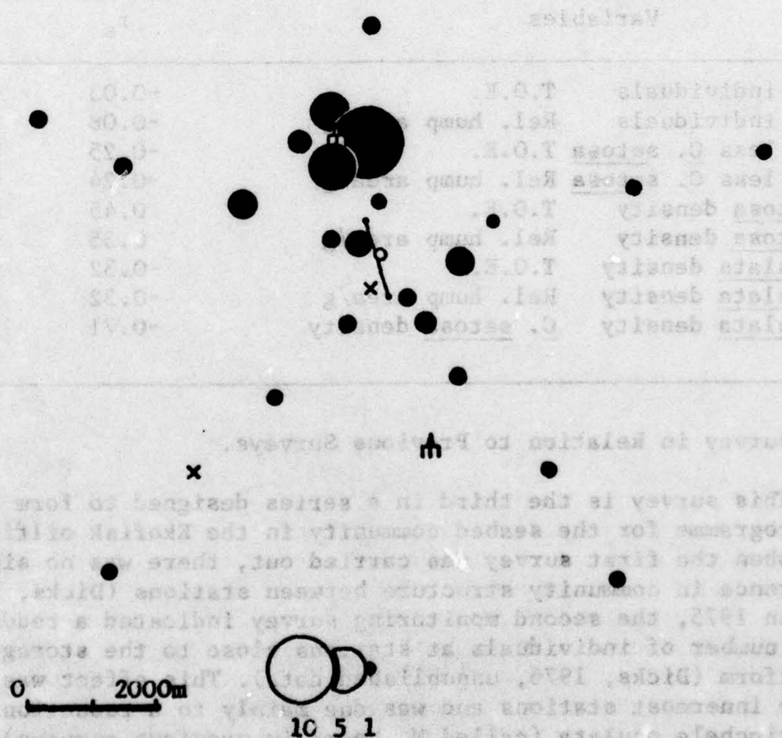

Fig. 22. nC_{18}/nC_{29} ratio at each station.

Correlation of Biological Data and Oil Analyses.

Using Spearman's rank correlation coefficient, the main biological variation has been compared with the oil analysis data.

This correlation analysis is summarised in Table 3. There is a significant negative correlation between Myriochele oculata density and weathered oil content as estimated by relative hump area per gram. A significant positive correlation between Chaetozone setosa density and weathered oil content is also indicated. Correlation of these species densities with total organic extractables was also significant (negative for M. oculata and positive for C. setosa), though for the reasons mentioned earlier, T.O.E. values should be treated with caution. Whilst not statistically significant ($p > 0.1$), there is some negative correlation between total number of individuals less C. setosa and weathered oil content. The correlation between total number of individuals and weathered oil content is not significant ($p > 0.3$).

Care must be taken in the interpretation of correlation analyses. The existence of a significant correlation in the data does not necessarily 'prove' a relationship in reality. From these results, however, it is valid to conclude that a relationship may well exist in the field between the oil content of sediments and the community structure of the seabed fauna.

Table 3. Correlation Analyses showing variables tested, rank correlation coefficient r_s and probability p of the observed correlation between ranks having occurred by chance.

Variables		r_s	p
Total individuals	T.O.E.	-0.03	0.44
Total individuals	Rel. hump area/g	-0.08	0.36
Total less C. setosa	T.O.E.	-0.25	0.1
Total less C. setosa	Rel. hump area/g	-0.24	0.12
C. setosa density	T.O.E.	0.45	0.01
C. setosa density	Rel. hump area/g	0.35	0.045
M. oculata density	T.O.E.	-0.32	0.06
M. oculata density	Rel. hump area/g	-0.32	0.06
M. oculata density	C. setosa density	-0.71	0.001

1977 Survey in Relation to Previous Surveys.

This survey is the third in a series designed to form a monitoring programme for the seabed community in the Ekofisk oilfield. In 1973 when the first survey was carried out, there was no significant difference in community structure between stations (Dicks, 1975).

In 1975, the second monitoring survey indicated a reduction in total number of individuals at stations close to the storage tank and B platform (Dicks, 1976, unpublished data). This effect was confined to the innermost stations and was due mainly to a reduction in numbers of Myriochele oculata (called M. heeri in previous surveys).

When comparing data from successive surveys, it must be borne in mind that sampling at the same time of year does not necessarily rule out the effects of natural fluctuations in species density, or possibly

species composition. Indeed the Ekofisk monitoring surveys have indicated large density variations in some species from year to year. For instance, *Chaetoderma nitidulum* has been found in increasing numbers from 1973 to 1977 and *Echinoid* juveniles were found in large numbers in 1975 but are only represented as rare occurrences in 1973 and 1977. Such variations as these occur uniformly throughout the area sampled and it is reasonable to conclude that they are natural fluctuations, probably unrelated to industrial activity.

Considerable long-term variations in *Chaetozone setosa* numbers have been found in recent years off the Northumberland coast. A decrease in density of larger species such as *Ammotrypane* (= *Ophelina*), *aulogaster* and *C. setosa* was thought to be related to warm winters since 1971 (Buchanan, 1978). The temporal variation in *Chaetozone setosa* densities in the Ekofisk area, however, is confined to a limited number of stations close to installations, and the increased density of this species is unlikely to be due to natural fluctuations.

SUMMARY

The 1977 survey indicated a clear reduction of population density at stations close to the central storage/production complex and B platform. A reduction in number of species is also apparent at these stations. The decrease in numbers of individuals is due mainly to a reduction of *Myriochele oculata* densities. A number of other species, for example *Owenia fusiformis* and *Amphiura filiformis* show a similar distribution. The decrease in numbers of species close to installations is due largely to a reduction in occurrences of species (particularly polychaetes) which have low densities in the area surveyed. Between the inner and unaffected outer stations there is a population density gradient and a gradient in the number of species encountered.

At stations which have low *Myriochele oculata* densities, there is a marked increase in the numbers of *Chaetozone setosa*. It appears that the *Chaetozone setosa* population has been able to take advantage in some way of the reduction in *Myriochele oculata* numbers.

Comparison with "baseline" data leads to the conclusion that the observed spatial variations are related to industrial activity in the area.

Comparison with data from 1975 indicates that the number of stations affected has increased from about 6 to 14. Station 3 near B platform was found to have a reduced population in 1975. Possible changes due to the blow-out on B platform in 1977 cannot be separated from changes which have occurred at all the inner stations since 1973.

The total area in which changes can be detected in 1977 extends about 2.5 km south-west and north-west and about 1.5 km north-east and south-east of the storage tank. To the north, the area affected is continuous with an area of reduced density around B platform which extends northward for about 2 km.

Hydrocarbon analysis has provided a semi-quantitative description of naturally occurring and petroleum-derived hydrocarbons at each sample station. The spatial variation in oil content closely follows the biological trends and is significantly correlated with the distributions of *Myriochele oculata* and *Chaetozone setosa*.

It is not possible to ascribe the biological effects specifically to oil pollution; however, the correlation between oil content and changes in population density means that oil pollution is possibly responsible for the observed effects. Other agents which may influence the seabed community are domestic waste and physical disturbance of the

sediment. No samples were analysed specifically for sewage contamination, but the absence of indicators such as tomato seeds in the biological samples does not point to a large input of domestic waste into the sediment. The possible alteration of current regimes close to installations should be considered. As only slight variation was found in the sediment samples studied, this mechanism is unlikely to be involved to any great extent.

Physical disturbance of the sediments close to the installations is a factor which should be seriously considered. A large number of anchors and other gear are frequently deployed in the area, probably resulting in considerable turning over of sediments and the production of clouds of silt in the water column above. Information from Phillips Petroleum Company indicates that the period leading up to the August 1977 survey was one of very high activity involving a large amount of barge movement and pipe-burying. The degree of sediment disturbance resulting from this is difficult to estimate accurately but it was certainly concentrated around the installations.

EVALUATION OF TECHNIQUES USED

The Day grab worked well on the sediments encountered in the Ekofisk area. It has been extensively used on a wide variety of substrates in recent years (see for example, Addy, 1975), and its robustness and simplicity of operation recommend it for continued use.

The monitoring aims of the present programme are to detect and quantify changes occurring in the locality of the installations. Consequently, the sample stations are all relatively close to the installations, the most remote being approximately 6.5 km away from the storage tank.

To date, the outer stations remain unaffected by industry-related changes in macrobenthic community structure, and it is appropriate to regard these stations as controls. This approach is justified largely by the results of Dicks' baseline survey of 1973 which found a uniform community throughout the whole area. If the affected area continues to increase, it may be necessary to expand the total area covered in order to sample surrounding control sites.

Once the layout of sample stations is determined, the choice of sieve mesh size and degree of sample replication are probably the most important factors to be considered when planning sample programmes.

If only widespread gross changes are to be detected, then the loss of information resulting from low numbers of replicate grab samples would be acceptable. However, in the survey carried out around the Ekofisk installations it was desired to detect small localised changes in the macrobenthic community at an early stage. To this end a fairly intensive sampling regime, involving ten replicates at each station, was employed. Species area curves for a range of stations are shown in Fig. 23. The rate of species recruitment with area is greater at station 1, suggesting that the rarer species are not as fully sampled at the outer stations. However, as only one or two species are recruited between the later replicates both in the species-rich station 1 and species-poor station 15, it is felt that most of the rarer species have been encountered.

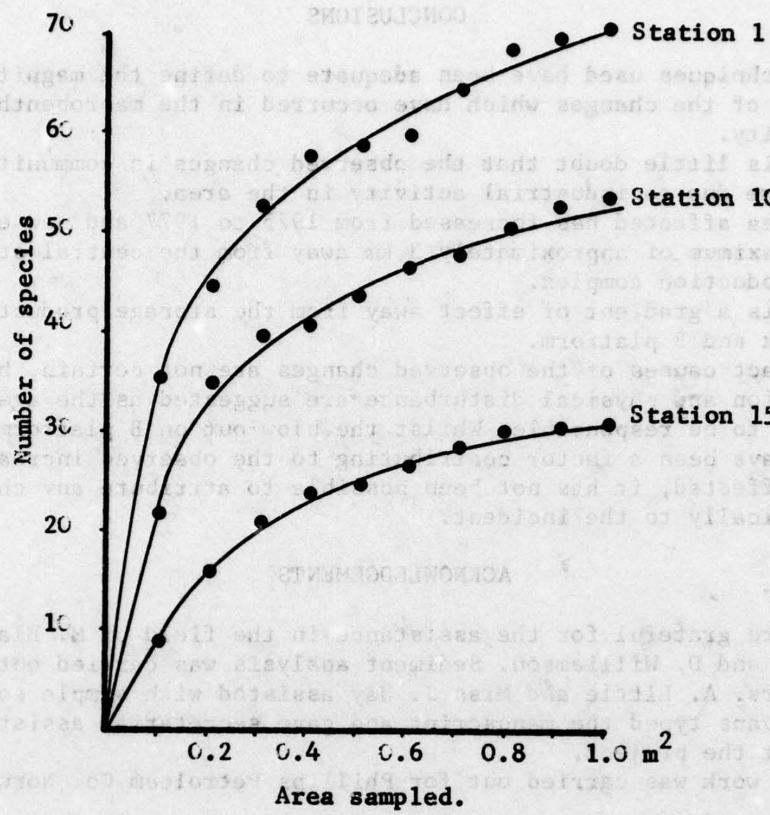

Fig. 23. Species-area curves for stations 1, 10 and 15.

The choice of sieve mesh size depends very much on the purpose of the survey. Birkett and McIntyre (1971) review some of the investigations which have been carried out into the effects of different mesh sizes on biomass and population density estimates. Use of a 1 mm mesh clearly results in the loss of small species and many juvenile individuals from the sample. If the population dynamics of the community is under investigation this would be a serious loss of information. Whilst it would be interesting to investigate possible effects of industrial activity on production and biomass, such studies are not required in a practical monitoring programme of the kind used so far in Ekofisk.

Data of the kind produced in this monitoring programme is very suitable for analysis by ordination techniques. This has not yet been carried out, though it is doubtful whether much more information would come out of such analysis than has already been produced by the use of distribution maps and regression analysis. The use of simple distribution maps has much to recommend it. It is felt that within the constraints of sample station layout, the information in Figs. 3 to 12 has produced a fairly clear indication of the extent and magnitude of the changes which have occurred.

Having defined the nature of the changes in terms of species composition and abundance, it may be useful in subsequent surveys to concentrate on delineating with more precision the area of seabed affected. With this aim it would be appropriate to establish additional sample stations between the radiating lines used so far.

CONCLUSIONS

1. The techniques used have been adequate to define the magnitude and extent of the changes which have occurred in the macrobenthic community.
2. There is little doubt that the observed changes in community structure are due to industrial activity in the area.
3. The area affected has increased from 1975 to 1977 and now extends to a maximum of approximately 3 km away from the central storage and production complex.
4. There is a gradient of effect away from the storage/production complex and B platform.
5. The exact causes of the observed changes are not certain, but oil pollution and physical disturbance are suggested as the agents most likely to be responsible. Whilst the blow-out on B platform may well have been a factor contributing to the observed increase in area affected, it has not been possible to attribute any changes specifically to the incident.

ACKNOWLEDGEMENTS

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Appendix. Table gives number of individuals per m^2 at each station. P = present.

Taxa / Stations	1	2	3	4	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Virgularia mirabilis	2	3	-	-	1	-	-	-	2	-	2	-	1	1	-	2	-	1	2	2	1	1	-	3	3	-
Cerianthus sp.	9	4	17	10	10	7	19	5	5	4	11	5	4	5	8	8	2	7	7	10	6	9	7	7	-	26
Anemone sp. 16.27	1	-	-	-	-	1	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nemertine sp.	-	-	2	1	2	2	1	1	2	2	-	-	4	-	2	2	3	-	1	-	1	-	1	-	-	3
Aphrodite aculeata	2	1	-	2	2	1	2	-	1	-	3	2	-	-	-	1	1	-	1	2	2	-	1	-	3	-
Harmothoe spp.	3	-	-	1	3	-	1	-	2	-	1	-	-	-	5	1	-	-	-	-	1	-	-	-	-	7
Sthenelais limicola	9	-	-	1	8	1	1	2	5	7	-	1	1	-	8	6	-	-	4	2	-	-	-	-	7	-
Pholoe minuta	55	10	16	12	81	13	189	40	22	37	225	55	9	6	18	33	25	18	29	14	18	35	44	53	20	56
Paramphinome pulchella	-	-	-	-	1	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Phyllodoce sp.	3	3	-	4	1	4	6	1	-	3	2	3	6	4	2	2	2	-	4	2	-	3	1	7	7	-
Hesionidae spp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
Eteone sp.	1	-	3	-	2	-	1	2	-	-	-	-	4	-	1	1	-	3	-	-	1	1	-	-	-	3
Syllidae spp.	1	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nephtys spp.	20	23	10	9	37	23	40	17	39	17	31	22	5	12	17	29	42	19	18	33	13	12	18	7	27	16
Ephesia gracilis	-	-	-	-	-	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Glycera sp.	7	4	3	2	8	11	26	15	6	9	18	18	26	-	4	8	10	4	15	8	[illegible]	4	5	10	3	7
Goniada maculata	65	48	17	29	91	69	81	36	64	67	71	52	30	-	78	84	73	32	75	71	41	37	27	7	43	26
Lumbrineris spp.	4	3	9	2	4	2	5	9	2	7	12	15	10	2	4	4	3	7	3	3	5	3	4	7	17	13
Scoloplos armiger	29	1	-	3	24	6	7	1	15	10	3	7	-	-	20	19	5	3	12	14	1	4	13	-	3	-
Spio filicornis	-	-	-	-	1	1	-	2	-	-	-	5	1	-	-	-	2	-	-	1	-	-	-	-	-	-
Spio multioculata	1	-	-	-	-	-	8	2	4	-	10	2	-	-	2	3	2	-	-	-	-	-	-	-	-	-
Spiophanes bombyx	-	-	-	-	-	-	-	-	-	-	1	-	-	-	3	-	-	-	-	-	-	-	-	-	-	-
Spiophanes kroyeri	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
Aonides paucibranchia	3	-	1	-	3	-	-	-	-	-	-	-	-	-	3	6	-	-	-	-	-	-	-	-	-	-
Polydora sp.	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Paraonis sp.	25	4	13	1	45	3	69	27	27	22	103	33	4	2	23	47	27	37	4	9	19	14	7	13	33	56
Aricidea sp.	4	4	-	-	3	-	1	-	-	-	-	-	-	-	1	2	-	1	4	-	-	-	-	-	-	-
Chaetozone setosa	20	15	356	24	21	39	178	179	7	15	136	157	451	270	14	20	37	472	19	8	35	58	95	533	30	63
Cirratulid spp.	1	9	4	2	6	5	10	1	6	6	41	9	2	13	9	25	10	2	4	-	5	-	-	-	-	-
Diplocirrus glaucus	[illegible]	-	-	-	[illegible]	[illegible]	-	-	[illegible]	[illegible]	[illegible]	-	-	-	[illegible]	[illegible]	1	-	[illegible]	[illegible]	-	-	-	-	-	-
Ophelia borealis	[illegible]	[illegible]	-	-	[illegible]	-	-	-	[illegible]	[illegible]	-	-	[illegible]	-	[illegible]	[illegible]	-	-	[illegible]	[illegible]	-	-	-	-	-	-
Ophelina aulogaster	1	-	-	-	-	3	5	3	-	3	1	2	-	-	5	5	-	-	1	-	-	-	1	-	-	-
Capitellid sp.	-	-	-	-	-	-	-	-	1	-	-	-	-	28	-	-	-	-	-	-	-	-	-	-	-	-
Maldanid spp.	2	-	-	1	1	-	-	-	2	1	2	1	1	-	2	-	-	-	1	1	-	-	1	-	-	-
Owenia fusiformis	59	18	-	-	60	27	41	9	63	61	17	19	2	-	33	34	14	1	38	18	7	1	2	-	7	-
Myriochele oculata	1043	559	48	66	1563	2700	1161	266	1635	1490	472	127	215	5	1611	2520	144	11	2840	867	318	149	136	27	267	283
Pectinaria auricoma	1	-	-	-	2	1	1	-	2	2	-	-	-	-	3	2	3	-	1	1	-	-	-	-	-	-
Sosane gracilis	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
Samytha sp.	1	-	-	-	-	-	3	-	-	-	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ampharete acutifrons	16	-	-	-	5	1	-	-	-	-	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ampharetid spp. juv.	-	3	2	-	38	3	14	2	1	1	11	2	1	-	1	8	4	4	4	-	-	1	4	-	13	13
Trichobranchus sp.	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	1	-	-	-	-	-	-	-	-	-
Lysilla loveni	-	-	-	-	-	-	2	3	-	1	1	1	-	-	1	1	2	-	-	-	-	-	-	-	-	-
Chone sp.	-	1	8	5	-	1	3	6	-	-	2	2	8	1	1	-	2	2	25	1	2	-	-	-	-	-
Sabellid spp.	34	3	6	3	18	3	32	5	2	4	15	5	4	1	21	32	9	1	-	16	6	9	4	7	20	7
Hydroides norvegica	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Spirorbis sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-
Polychaete 68	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

<u>Appendix</u> (continued)

Taxa / Stations	1	2	3	4	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
<u>Phascolion strombi</u>	2	1	-	-	3	2	3	2	-	2	5	3	-	-	4	-	2	-	2	1	1	-	1	-	-	3
Cumacean spp.	6	5	4	3	16	7	8	6	5	4	5	-	6	1	12	5	7	2	4	5	-	3	6	-	3	-
<u>Ampelisca</u> sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-
Hyperiid sp.	-	-	-	-	1	1	-	1	-	-	-	1	1	-	-	-	-	-	1	-	-	1	-	-	-	-
Oedocerid spp.	-	-	-	1	2	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
Lyssianisid spp.	4	11	18	39	18	18	24	31	19	10	51	19	34	40	12	15	32	19	5	8	9	27	66	20	7	16
<u>Podoceros</u> sp.	-	-	1	-	-	-	-	-	-	-	-	1	1	3	-	-	-	1	-	-	1	-	2	7	-	-
<u>Corophium</u> sp.	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
<u>Meganictiphanes norvegica</u>	-	-	1	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	1	-	1	-	-	-	-
<u>Crangon allmani</u>	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	1	-	-	-	-	-	-
<u>Pagurus</u> sp.	2	-	-	-	-	-	-	-	-	2	-	-	-	1	2	1	-	-	-	-	-	1	-	-	3	3
<u>Macropippus</u> sp.	-	-	-	2	1	-	-	-	-	-	-	-	1	1	1	-	-	1	-	-	-	-	-	-	-	-
<u>Hyas ?coarctatus</u>	4	-	-	-	1	-	-	1	1	-	-	-	-	-	-	1	-	-	1	-	-	-	1	-	-	-
Crustacean 7.4	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ostracod spp.	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Crustacean sp. 62	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<u>Chaetoderma nitidulum</u>	16	15	10	4	28	20	73	21	8	6	41	12	13	-	16	20	16	11	16	11	9	9	12	17	17	16
<u>Clathrus turtonis</u>	1	-	-	-	1	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
<u>Eulima trifasciata</u>	1	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-
<u>Balcis</u> sp. 26	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<u>Natica montagui</u>	2	-	-	-	2	-	8	6	-	1	6	2	-	1	1	5	2	-	6	1	-	12	4	3	7	7
<u>Natica alderi</u>	2	-	-	-	2	1	1	1	-	-	1	-	-	-	-	1	2	3	-	-	-	-	2	-	-	-
<u>Natica</u> spp. juv.	2	3	-	4	2	3	1	2	4	3	-	7	1	-	-	-	10	6	-	4	12	-	2	3	-	-
<u>Colus gracilis</u>	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<u>Buccinum undatum</u>	2	-	-	-	-	-	-	1	-	2	-	-	1	-	-	-	-	-	-	-	1	-	-	-	-	-
<u>Acteon tornatalis</u>	3	1	-	-	2	2	1	-	-	-	-	1	-	-	3	2	4	-	4	-	1	1	-	-	-	-
<u>Cylichna cylindracea</u>	2	3	-	1	1	1	1	1	5	-	1	-	-	-	-	1	-	1	-	-	1	2	1	-	3	-
<u>Retusa ?umbilicata</u>	-	-	-	-	-	-	-	-	1	-	-	-	-	-	1	-	-	-	-	-	-	1	-	-	-	-
<u>Diaphana minuta</u>	-	1	-	-	1	3	-	-	-	-	-	4	-	-	-	-	-	-	1	-	2	-	-	-	-	-
<u>Philine</u> spp.	-	-	3	6	-	-	-	4	-	-	-	-	-	11	-	-	-	-	-	-	10	5	6	10	-	10
[illegible] sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nudibranch 41.41	-	-	-	-	1	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
Gastropod sp. 50	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Scaphopoda spp.	3	3	1	-	3	1	-	1	2	3	5	4	-	-	1	4	4	2	3	4	2	2	-	-	3	3
<u>Modiolus</u> spp. juv.	-	-	-	-	1	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
<u>Musculus niger</u>	-	-	-	-	-	-	-	-	1	2	1	1	-	-	-	-	-	-	-	1	-	-	2	-	-	-
<u>Musculus</u> sp. juv.	2	-	-	-	-	-	1	-	1	-	4	-	-	-	-	3	-	-	1	-	-	2	1	-	-	-
<u>Astarte borealis</u>	-	-	-	-	-	-	1	1	-	-	-	1	-	6	-	-	-	-	-	-	-	2	-	-	-	-
<u>Astarte</u> spp. juv.	-	-	-	-	-	-	-	-	-	-	3	-	-	-	1	-	-	-	-	-	-	-	1	-	-	-
<u>Arctica islandica</u>	18	8	52	5	26	11	18	9	19	13	11	10	7	157	20	14	9	11	11	17	1	13	11	47	13	53
<u>Thyrasira flexuosa</u>	12	20	2	5	10	11	13	7	4	5	17	6	10	-	8	6	7	6	10	7	5	7	1	10	7	-
<u>Mysella bidentata</u>	1	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
<u>Montacuta substriata</u>	12	-	-	-	10	-	-	-	17	-	-	-	-	-	17	-	-	-	-	4	-	-	-	-	-	-
<u>Cardium echinatum</u>	-	-	-	-	-	-	-	-	1	-	-	-	-	1	1	-	-	-	-	-	-	-	-	-	-	-

Appendix (continued)

Taxa	Stations	1	2	3	4	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Dosinia lupinus		1	-	-	2	1	1	-	-	-	1	1	1	-	-	-	3	-	-	-	1	1	-	-	-	-	-
Venus casina		-	1	1	3	-	-	-	-	-	5	-	3	2	-	-	-	-	-	-	1	2	-	-	-	-	-
Venus ovata		1	-	-	2	-	2	-	-	-	1	-	-	1	1	-	-	-	1	1	1	1	4	2	-	-	-
Venus spp. juv.		8	-	-	-	-	1	2	-	7	-	1	-	-	-	4	1	-	-	3	-	-	5	3	-	-	3
Mysia undata		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
Spisula elliptica		-	-	1	1	-	-	-	-	-	-	-	-	-	1	-	-	-	1	-	-	1	-	2	-	-	-
Gari fervensis		-	-	-	-	-	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	13	-
Abra prismatica		72	20	3	9	61	48	46	42	24	14	15	13	4	-	17	26	28	5	52	46	33	34	42	-	7	16
Cultellus pellucidus		5	14	10	8	11	8	22	20	5	4	21	14	8	4	1	1	14	21	2	2	29	16	13	13	30	33
Mya spp.		-	4	6	9	-	3	5	4	4	2	7	1	2	77	-	3	2	6	1	-	4	2	6	27	10	10
Hiatella arctica		3	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Phoronis sp.		2	-	-	-	-	-	3	-	-	-	6	-	-	-	-	2	-	1	-	-	-	-	-	-	-	-
Cnaetognatn sp.		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Astropecten irregularis		-	4	5	-	1	1	2	3	5	2	2	4	-	-	1	1	11	1	1	2	4	4	1	3	7	3
Luidia ?ciliaris		-	-	-	-	-	1	-	-	1	-	-	-	-	-	-	-	-	-	1	1	-	-	-	-	-	-
Amphiura filiformis		49	14	-	-	57	8	11	-	35	17	6	6	-	-	71	56	7	-	15	12	-	-	1	-	-	-
Ophiura affinis		8	3	-	5	3	6	7	4	4	5	3	-	6	2	8	4	4	1	5	3	3	7	4	-	-	3
Ophiura ?robusta		-	-	-	-	1	-	2	-	-	-	-	-	-	-	2	1	-	-	1	-	-	-	1	-	-	-
Ophiuroid juv. spp.		119	60	52	70	132	127	156	90	178	186	75	63	62	100	216	221	73	25	156	84	65	91	100	70	60	26
Echinocardium cordatum		1	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Echinocardium flavescens		3	-	-	-	2	-	-	-	2	-	-	-	-	-	2	-	-	-	-	1	-	-	-	-	-	-
Echinoid spp. juv.		10	3	-	-	10	-	2	-	-	-	7	-	-	-	4	5	4	-	4	-	-	-	1	-	-	-
Labidoplax ?buski		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
Pelonaia corrugata		4	-	-	-	3	-	-	1	1	-	5	1	-	-	1	1	-	-	1	-	-	2	1	-	-	-
Pleurogonid spp.		31	-	-	-	39	4	6	-	15	5	2	-	-	-	31	14	7	-	-	-	-	-	1	-	-	3
Ascidian sp. 49		2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pleuronectid sp. juv.		-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Ammodytes sp.		-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	1	-	-	-	-	-	-	-	-
Foraminifera		P	-	P	-	P	P	P	P	P	P	P	P	P	-	P	P	P	P	P	P	P	P	P	P	P	P
Tubularia indivisa		-	-	-	-	P	-	-	-	-	-	-	-	-	P	-	-	-	-	-	-	-	-	-	-	-	-
Hydractinia ?echinata		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	P	-	-	-	-
Alcyonium digitata		-	-	-	-	P	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Alcyonidium parasiticum		-	-	-	-	P	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bryozoan sp. 17		P	-	-	-	-	-	-	-	-	P	-	P	-	-	-	F	-	-	-	-	-	-	-	-	-	-
Bryozoan spp.		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	P	-	-	-	-	-	-	-
Copepod sp.		28	8	13	28	31	16	38	27	111	23	36	7	11	10	21	27	29	13	14	7	7	24	44	20	13	7
Paint flecks		P	-	P	-	-	P	P	-	P	P	-	P	-	P	P	P	P	P	-	-	-	-	P	P	P	-
Yellow balls		-	-	-	P	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	P	-	P	-	-
Purple stones		-	-	-	P	-	-	P	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

THE EFFECTS OF THE EKOFISK BLOWOUT ON HYDROCARBON RESIDUES IN FISH AND SHELLFISH

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ABSTRACT

Demersal fish were trawled in the Ekofisk area in May just after the Ekofisk Bravo well was capped and again some two months later in July. In addition, cages containing mussels were suspended in the water column near the bottom and recovered a few days later. The fish flesh was assessed for oily taints after cooking and samples of muscle and liver tissues were analysed for aliphatic and aromatic hydrocarbons. Although two samples of haddock caught initially showed signs of tainting at a low level, no taint was detected two months later. On both occasions the alkane concentrations in muscle and liver remained very similar to those found some years earlier during a baseline survey covering the North Sea. In May, but not in July, some analyses of the gut contents showed the presence of oily residues. The tissue samples which were anlaysed for selected two- to five-ring aromatic components gave individual concentrations below one nanogramme.

INTRODUCTION

The North Sea is one of the most intensively fished areas in the world (Steele, 1974) and provides the U.K. with a valuable fishery for pelagic and demersal fish and shellfish (Table 1). It is not surprising, therefore, that following the first major offshore oil spill incident in the North Sea related to petroleum production, which occurred at the Ekofisk Bravo platform on 22nd April 1977, there was concern to establish whether there were any serious effects on the ecosystem itself or whether the quality of commercially important species for human consumption was in any way affected. Ekofisk is included in that wide area of the North Sea in which mackerel spawn, usually beginning sometime in May, and it is also close to the Great Fisher Bank but it does not contribute in large measure to the U.K. catch and there is no shellfish fishery (Table 1). The most important species in the U.K. catch there in April and May are cod, haddock, plaice and sprat.

The area affected by oil slicks up to the time the well was capped on 30th April 1977 was largely to the north and east of the platform (Fig. 1). As the results of investigations in the area became known, it seemed that the nature of the crude, the conditions of the blowout, the weather and the hydrography had combined fortuitously to reduce the amount of crude oil entering the water column and to assist the natural, physical dispersive processes within the water mass. Consequently, it was believed that the potential danger for the biological resources of the area was reduced.

Perhaps partly because Ekofisk is near to a number of different national licensed zones (Fig. 1), various national groups participated in different sampling and analytical programmes, the results of which are now being correlated and summarised following a recent Workshop in Norway. Part of the U.K. investigations carried out over a wide area around Ekofisk, were concerned with analysis of hydrocarbon residues in marine organisms. The first U.K. fisheries research vessel on the scene was CORELLA (Ministry of Agriculture, Fisheries and Food, Lowestoft) which participated in a coordinated survey programme, during 28th and 29th April, with two Norwegian research vessels, G. O. SARS and JOHAN HJORT. Fish and shellfish were collected by bottom trawl at two positions (Fig. 2), one inside and the other outside the area covered by the slick at that time. The details of this work will be reported elsewhere (Law, 1978). During 3rd to 5th May, the EXPLORER (Department of Agriculture and Fisheries for Scotland, Aberdeen) carried out a limited research programme and collected fish by bottom trawl at five positions (Fig. 2), one outside and the remainder inside the area which had been covered by the slick. A part of the results from this cruise have been reported previously (Mackie et al., 1978). Finally, between 4th and 13th July as part of an investigation of the longer term fate of the oil, the G. A. REAY (Ministry of Agriculture, Fisheries and Food, Aberdeen) collected fish by bottom trawl at three positions (Fig. 2), one inside and the others outside the area originally covered by the slick. In addition, cages containing mussels were deployed on moorings and retrieved later from eight positions (Fig. 2).

This report is concerned primarily with the interpretation of the analyses for hydrocarbon residues in samples from the last two cruises and particularly in the tissues of fish of commercial value. Some of the fish caught by the EXPLORER were assessed later in the laboratory for oily taints but those caught by the G. A REAY were tasted on board.

METHODS

Most of the methods of sampling and analysis have been described elsewhere (Mackie et al., 1974; 1977; 1978) and are dealt with only

briefly below. The trawl caught fish were wrapped in clean aluminum foil, frozen whole as soon as possible after catching and subsequently stored at -30^{o} until required. Tissues for analysis were excised in the laboratory while the fish were still partially frozen. Alternatively, the tissues were excised fresh aboard ship and treated as above.

Mussels, collected a few days earlier on the west coast of Scotland, were kept in tanks supplied continuously with the vessel's pumped sea water supply whilst at sea. Ten animals were placed in plastic-coated wire cages, deployed on moorings just above the bottom, and recovered between 46 and 120 h later. The mussels were frozen whole and the entire shell contents analysed later. Reference samples were removed from the shipboard tank at the beginning and end of the mooring programme.

Squalane (1 μg) was added to all tissues before extraction (Bligh and Dyer, 1959) and aliphatic and aromatic fractions were isolated (Mackie et al., 1974) for analysis by gas-liquid chromatography (GC) on glass capillary columns. A 30 metre column coated with OV-101, programmed from 90^{o} to 280^{o} at 3^{o}/min, was used for alkane analysis (C_{15} to C_{33}) and a 15 metre column coated with SE-52, programmed from 100^{o} to 200^{o} at 2^{o}/min, was used for the aromatic fraction. In both cases, the carrier gas was oxygen-free nitrogen flowing at 0.75 ml/min, with an inlet split ratio of 15:1.

Samples of fish fillet were cooked on a steam bath in closed glass casserole dishes either in the laboratory or aboard ship and assessed for oily taints by experienced tasters (Howgate et al., 1977).

RESULTS AND DISCUSSION

Taint Assessment

The laboratory panel tasted haddock, plaice, lemon sole and gurnard from the May samples which immediately highlighted one of the difficulties with this type of assessment. Fish from different areas or fishing grounds have different intrinsic flavours and the panel had had no previous experience of fish from the Ekofisk area. They showed considerable doubt in making positive recognition of oily taints above an unfamiliar background flavour, although there was at least one positive response from the panel to each of the 18 samples tested. In view of the uncertainty, it was decided arbitrarily to verify an oily taint only if more than half the panel gave a positive response. On this basis, taint was identified only in haddock from stations E2 and E4 (Fig. 2). In neither of the cases was the opinion unanimous and it seems likely that the level of taint detected was close to the threshold of the trained panel. It would have been of little consequence to the average consumer and probably would have gone unnoticed.

The shipboard panel was unanimous in making negative responses to all of the July samples of haddock and cod tasted from station G3 and G8 (Fig. 2). It was noted that the flavour of the July fish was particularly bland, a fact which should have made any oily taint easier to detect. No further assessments were made at the laboratory in Aberdeen.

Fish Analyses

A relevant and useful indication of the possible effects of exposure to crude oil in the diet or in the surrounding water on aliphatic residues in the liver and muscle tissues of cod was provided by some earlier experimental studies reported briefly by Hardy et al., (1974). Little change in n-alkane composition or concentration was observed in muscle tissue even after 6 months exposure to water circulated from beneath a slick of a topped Kuwait crude. However, a small but significant increase was noted in the liver tissue within 2 months. Exposure to small quantities of the same oil in the diet caused, within 2 months, a larger increase in concentration of n-alkanes in the liver tissue and a marked change in composition, although no effect was noted in the muscle tissue even after 6 months exposure. These results are summarised in Fig. 3.

Between 1971 and 1975, before the acceleration of offshore production in the North Sea, this laboratory carried out more than 200 analyses representing 19 species of fish from 17 different areas or fishing grounds in the coastal waters and seas surrounding the U.K. (Whittle et al., 1977), as part of a survey programme covering hydrocarbon residues in the biota, water column and sediment. These provided for future reference, the concentrations of aliphatic hydrocarbons, particularly the n-alkanes, present at that period in the muscle and liver tissues of the fish. The most relevant results from the survey for comparison with fish samples caught and analysed after the Ekofisk blowout are those from a variety of open sea sites. All these n-alkane analyses are summarised in Table 2 where E1, G1 and G8 represent stations beyond the original area of the slick (Fig. 2). Haddock provides the most complete set of samples for comparison. As expected, there is considerable variation within the Ekofisk values. This degree of variation is a common feature of analyses of field samples. However, compared with the range experienced in the survey, there is no discernible and statistically significant relative increase in total n-alkane concentrations in fish from within the original slick area, obtained during the May sampling, and they do not appear to be consistently higher than either the samples from outside the slick area or those taken in the July sampling. Thus, there is no evidence of changes in alkane concentration analogous to those observed in the cod kept in contaminated water or fed a contaminated diet. Comparison of the n-alkane distributions within the various Ekofisk samples and with the survey

data, did not reveal any clear modifications of the pattern to the extent which was observed in the cod experiments or any obvious and consistent deviation from previous experience reported in the survey results.

Besides liver and muscle, a number of other tissues and organs such as gills, gonad and gut (including stomach and hind gut) were analysed from the May samples as well as gut from the July samples (Table 2). Comparison of the gross alkane values, the n-alkane distributions or the phytane/octadecane ratios, did not prove particularly helpful in distinguishing which samples, if any, contained hydrocarbon residues from the Ekofisk crude. However, detailed comparison of the chromatograms of the tissue samples with the crude showed unmistakable evidence of the Ekofisk fingerprint in the branched alkane pattern ranging between C_{14} and C_{19} (Fig. 4) in haddock gut (E2, E4 and E6) and mackerel gut (E1) but not in plaice or in any of the July samples. Chromatograms of other tissues such as gonad and liver did not show the branched alkane fingerprint but, instead, the so-called 'hump' or unresolved complex mixture (URCM) often regarded as characteristic of earlier exposure to petroleum hydrocarbon contamination, was sometimes prominent although this was not so in most of the July samples.

Analysis of the aromatic fraction by GC revealed no evidence of naphthalene and substituted naphthalenes, the major component of the crude, in any of the July samples and most of the May samples. However, where suspected in the latter, total concentration was less than two to three nanogrammes. The GC analysis did indicate that the preparatory column chromatography on silicic acid did not provide a clean aromatic fraction since both less polar and more polar components were identified also in the fraction. Thus, although earlier tests with authentic standards had yielded clean aromatic fractions, a more rigorous clean-up procedure is required for the lipid extracts of fish tissues. A few fractions from the July liver samples were examined in more detail by mass spectrometry (MS). Specific mass ions representing naphthalene, mono- and di-methyl naphthalenes, 3-ring systems and their mono-methyl substituents, dibenzothiophene, 4-ring systems, and 5-ring systems were monitored during GC analysis. Total concentrations were found in the range 10^{-3} to 10^{-4} μg/g wet weight tissue. In all cases naphthalene and substituted napthalenes are the major components.

Mussel Analyses

It has been suggested that mussels might be effective organisms for indicating the extent of contamination of an area with petroleum, as well as other pollutants, after suitable analysis. We advanced and modified some plans to test out this idea by taking the opportunity, at relatively short notice, to deploy cages of mussels in the Ekofisk

area (Fig. 2). We hoped to evaluate whether it was a useful and practical approach to assess the degree of recovery of an area subjected to a specific incident. The alkane analyses from the moorings and from the samples taken at the beginning and end of the mooring programme (controls), as well as other relevant information such as various alkane ratios, and the sequence of mooring and recovery, are summarised in Table 3.

The period of exposure varied from 46 to 120 h and there were no mortalities among the mussels retrieved. The n-alkane totals are remarkably similar throughout, ranging only between 0.2 and 0.4 μg/g wet weight, and were low compared with 1.7 μg/g wet weight obtained for a sample from the same source on the Scottish west coast during the U.K. survey programme. In contrast, the concentrations of pristane and phytane vary by factors of 15 and 20 respectively and their abundance relative to n-C_{17} and n-C_{18} also varies widely. Numerous organisms prey to mussels are rich in pristane and their availability could be expected to influence the pristane concentration and thus account for that observed fluctuation in concentration. It has been suggested that phytane is not of marine biogenic origin but arises from exogenous sources, perhaps primarily from petroleum. Also it is degraded less readily than normal alkanes of similar boiling point and so might be expected to be more persistent. Thus, the phytane/n-C_{18} ratio should provide a useful clue to the presence of petroleum components. On this basis, the samples from the July sampling programme in which the ratio exceeds 1.0 tend to be closest to the platform along the north/south axis. This distribution corresponds roughly with the higher fluorescence values for sub-surface water samples, the higher surface tar concentrations and also includes the highest surface film concentrations as shown in Fig. 5 (Mackie et al., 1978). Although the n-alkane distributions of the mussel samples show different relative proportions of the various homologues, they are not strongly indicative of a major presence of degraded or weathered crude components. A similar conclusion can be drawn from a detailed examination of the chromatograms.

The chromatogram fingerprints fall into two major groups (Fig. 6); those which feature prominently what are probably biogenically derived olefins (G4, G7, G8) and differentiated clearly from the initial control, even after the relatively short period of 46 h in the sea and, those (G21, G23, G34, G35) in which the same biogenic components are present but identified less easily. They show instead a marked presence of the lower n-alkane and branched alkane homologues similar to those usually found in crude oil distributions. This latter group includes most of the samples with the higher phytane/n-C_{18} ratios. However, a similar distribution was noted also in the final control sample. Thus, although the controls did not differ in total n-alkane concentration during the mooring programme, the marked differences in their detailed

alkane patterns makes interpretation of the results much more difficult. The changes in the composition of the shipboard mussels could have been due to contamination of the sea water supply aboard the ship, from the ship's pumps for instance, or they could have been a true reflection of the quality of water pumped aboard. If shipboard contamination had caused the change, the mussels would have been contaminated to a greater or less extent before deployment, depending on the length of time spent in the shipboard tank. Whatever the explanation, the differences between all the patterns suggest strongly that mussels may acquire a different alkane composition quite rapidly. Our analyses show that both biogenic and petrogenic components were taken up by the mussels during the relatively short time of mooring without increasing the total hydrocarbon load. Both observations are compatible if there is a sufficiently rapid turnover of tissue hydrocarbons without any accumulation. Perhaps they are in some form of dynamic equilibrium with the environmental exposure, at least at the concentrations encountered in this case, but we know little of the limiting rates of such a process.

Experiences with GC of the aromatic fraction were much as described earlier for the fish samples. Two detailed analyses were carried out by MS as before on samples G4 and G34. The concentrations were in the 10^{-4} to 10^{-3} $\mu g/g$ wet weight ranges respectively, the latter being due largely to an 18-fold increase in concentration of naphthalene plus substituted naphthalenes, confirming the contamination pattern noted from the detailed alkane composition described below.

CONCLUSIONS

The concentrations of n-alkanes in the liver and muscle tissues of the fish caught in the Ekofisk area soon after the flow of oil was halted, and again some two months later, were within the range experienced in the past from samples caught in the open seas around the U.K., so that there appeared to have been no significant addition to the overall body burden as a direct result of the incident. Law (1978) reached the same conclusion from his analyses. However, the alkane fraction did show evidence, particularly in haddock, that in May the fish had picked up Ekofisk oil via the digestive tract. Other tissues such as liver and gonad showed evidence of the residual components of exposure to some type of oil although the identity could not be established. It was not possible to decide whether the distribution in these other tissues was the result of modification by processes of assimilation and deposition or metabolism and depuration, or of course, interaction between them all on a petroleum substrate which could have been available to the fish either in the food or by absorption through the gills from the surrounding contaminated water. Since in the May samples, Ekofisk oil was identified in the digestive tracts of haddock and possibly mackerel, but not plaice, it is interesting to speculate on the origin of this oil. Although the stomach content of the haddock was more heterogeneous than the mackerel some of the contents were

common to both samples whereas the plaice which spends most of its time close to or buried in the bottom were distinctly different. Now, from the results of the analysis of the contents of suspended sediment traps deployed during the May programme, the highest concentrations of particulate oil in the water column were found nearer the surface (33 m above bottom), even though the hydrographic data show that the water column was well mixed (Mackie et al., 1978). It seems at least possible then that both the haddock and mackerel ingested food organisms which had been contaminated previously with oil in the surface waters perhaps by adsorption on their surfaces or by ingestion themselves. Unfortunately, the number of sediment traps which can be deployed is limited at the moment. Deployment of more traps in the future should help to identify the particulate residues more accurately and enable a better assessment of the availability of particulate oil to animals in the field.

To all intents and purposes the analyses of the July samples appeared normal and no oily residues were identified in the guts. The aromatic components were at extremely low concentrations which must be within the background range and no oily taints were detected. Thus, the effects which were noted in the May samples, such as the oily residues in the guts, did not persist and, fortunately, the low level of taint identified was probably of little consequence to the consumer.

The use of caged mussels raised more questions than it answered. Clearly, the hydrocarbon load available to them in July was not exceptional and biogenic components were prominent. However, the apparently rapid change in their detailed alkane composition over the 160 h of the programme and the 5-fold difference in concentration of alkanes in samples taken from the same unpolluted areas at different times, suggests some limitations on the value of using mussels in the so-called 'mussel watch' programmes. In part, their selection as an indicator species is based on the belief that they act as integrators of the degree of contamination over a long period of exposure in a particular environment. Our results suggest that the detailed alkane composition reflects the most recent history of exposure of the animal but that the overall n-alkane concentration remains fairly constant at least under the conditions of exposure pertaining at the time of our experiments. On the other hand, the aromatic fraction increased by a factor of about 8 in the animals thought to have been exposed to contaminated sea water, and most of the increase was due to naphthalene and substituted naphthalenes. The higher values close to the Ekofisk complex for many of the environmental parameters measured in the July programme, the mussel results and the observations of small fresh slicks in the area suggests that in addition to the residues remaining from the Bravo blowout, the background there may be enhanced by fairly frequent but minor incidents generated by production and traffic.

The conditions of the Bravo incident mitigated the impact of the oil on the surrounding environment. Some fish tissue hydrocarbons were modified in the immediate aftermath of the incident but the effect on the quality of the fish as food, as measured by the chemical and sensory techniques used, was not significant and conditions reverted to normal rather quickly. It would be dangerous to assume however that incidents of this type pose no threat at all to fisheries and to marketable catch and allow a sense of complacency to develop since it is unlikely that the same set of fortuitous circumstances will be repeated.

ACKNOWLEDGEMENTS

The sampling programme was carried out in conjunction with staff of the Marine Laboratory, Department of Agriculture and Fisheries for Scotland, Aberdeen and the Fisheries Laboratory, Ministry of Agriculture, Fisheries and Food, Burnham-on-Crouch, and with the support of the Marine Research Institute, Bergen. Both Dr. A. D. McIntyre and Dr. J. M. Davies of the Marine Laboratory advised and made sampling equipment available. Staff of the Marine Laboratory and the Fisheries Laboratory, Lowestoft, provided the U.K. catch data.

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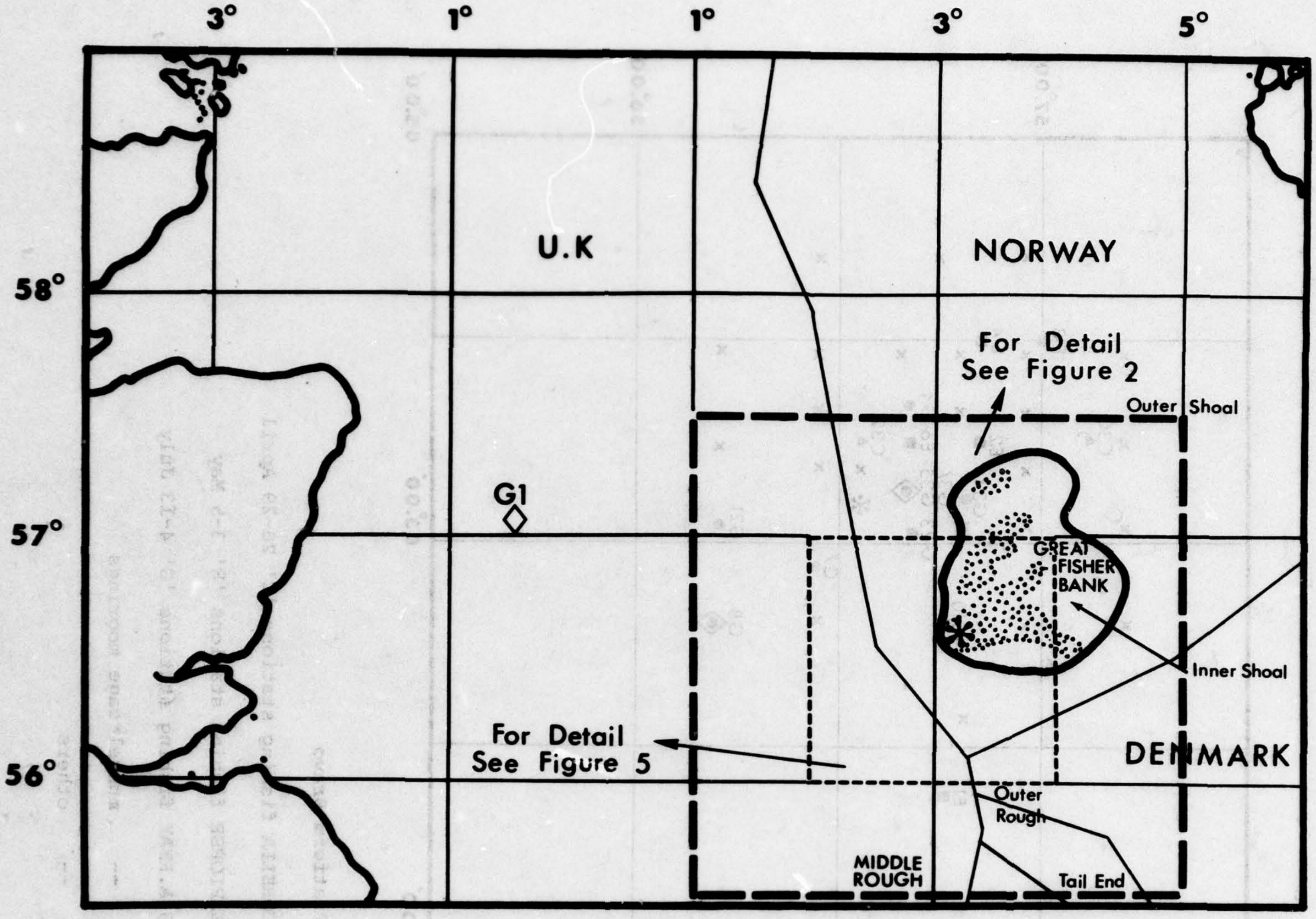
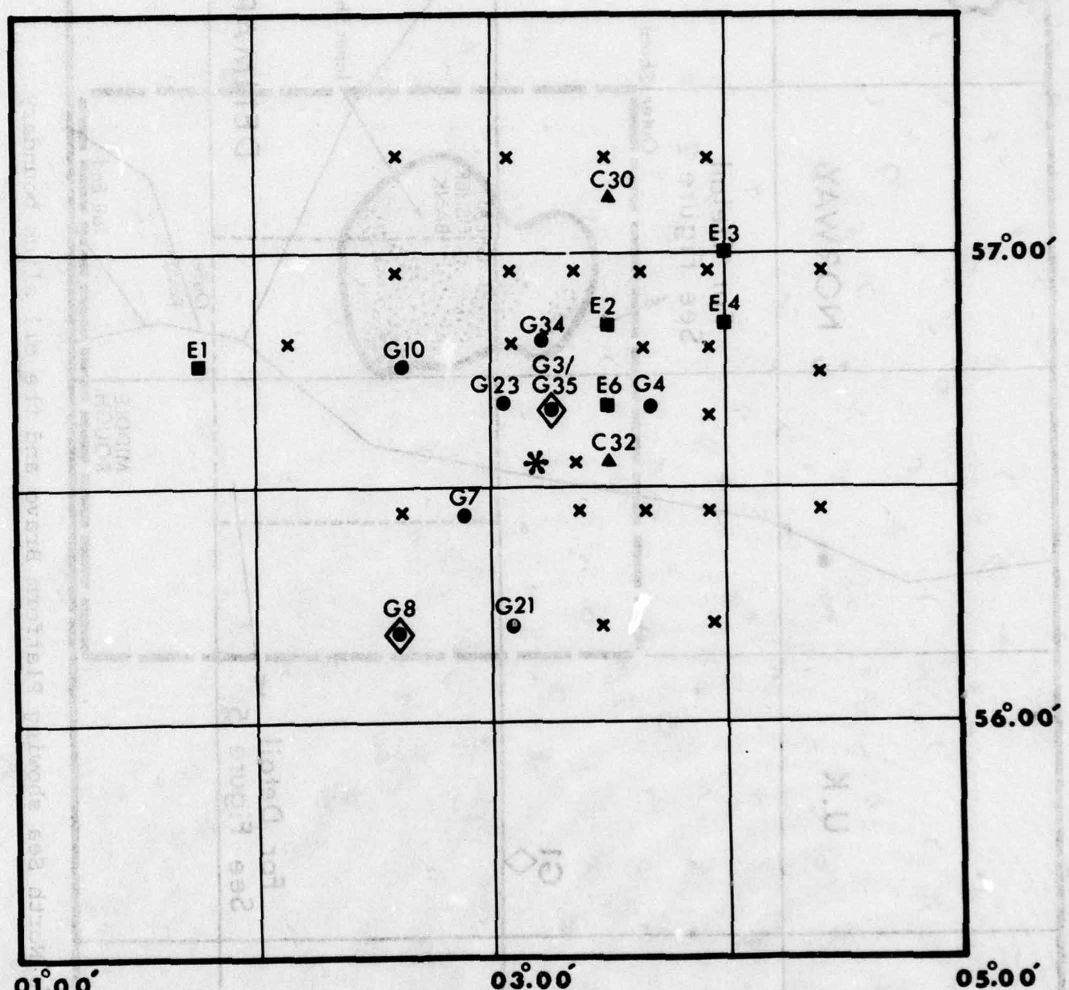


FIGURE 1. The Ekofisk area in the North Sea showing Platform Bravo and the oil slick boundary.

- Thin oil slick boundary over first 5 days after blowout.
- Thick slick.
- National zones.
- Platform Bravo.
- Area of 144000 square nautical miles around Ekofisk.
- Station G1, G.A.Reay cruise July 1977.

FIGURE 2

Sampling Positions



✱ Platform Bravo

▲ CORELLA fishing stations 'C' 28-29 April

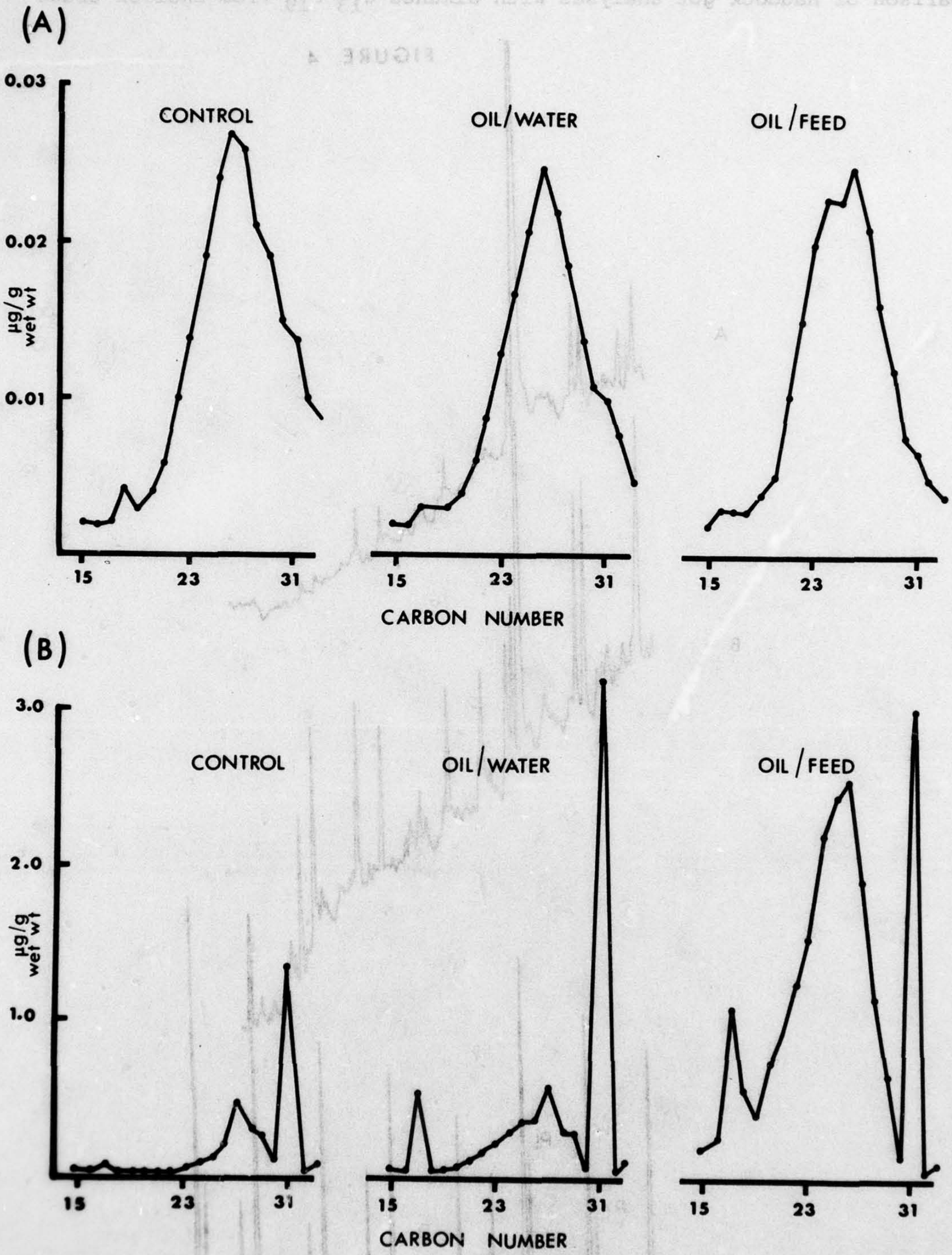
■ EXPLORER fishing stations 'E' 3-5 May

◈ G.A.REAY fishing stations 'G' 4-13 July

● -- mussel cage moorings

✖ -- others

FIGURE 3. Comparison of n-alkane profiles in (A) muscle and (B) liver tissues of cod kept in different conditions.



The fish were kept for 62 days on:

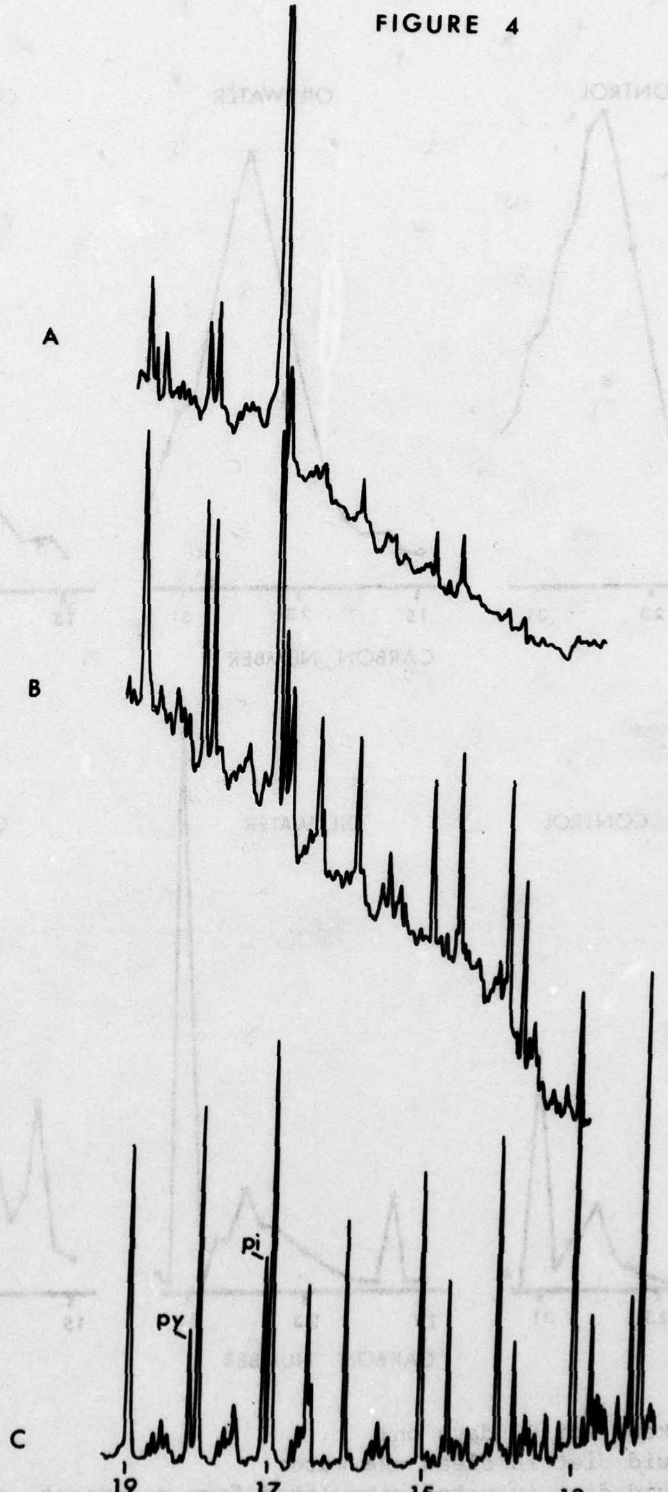
CONTROL - squid diet in clean sea water

OIL/WATER - squid diet in water circulated form underneath an oil slick

OIL/FEED - squid diet with added crude oil in clean sea water

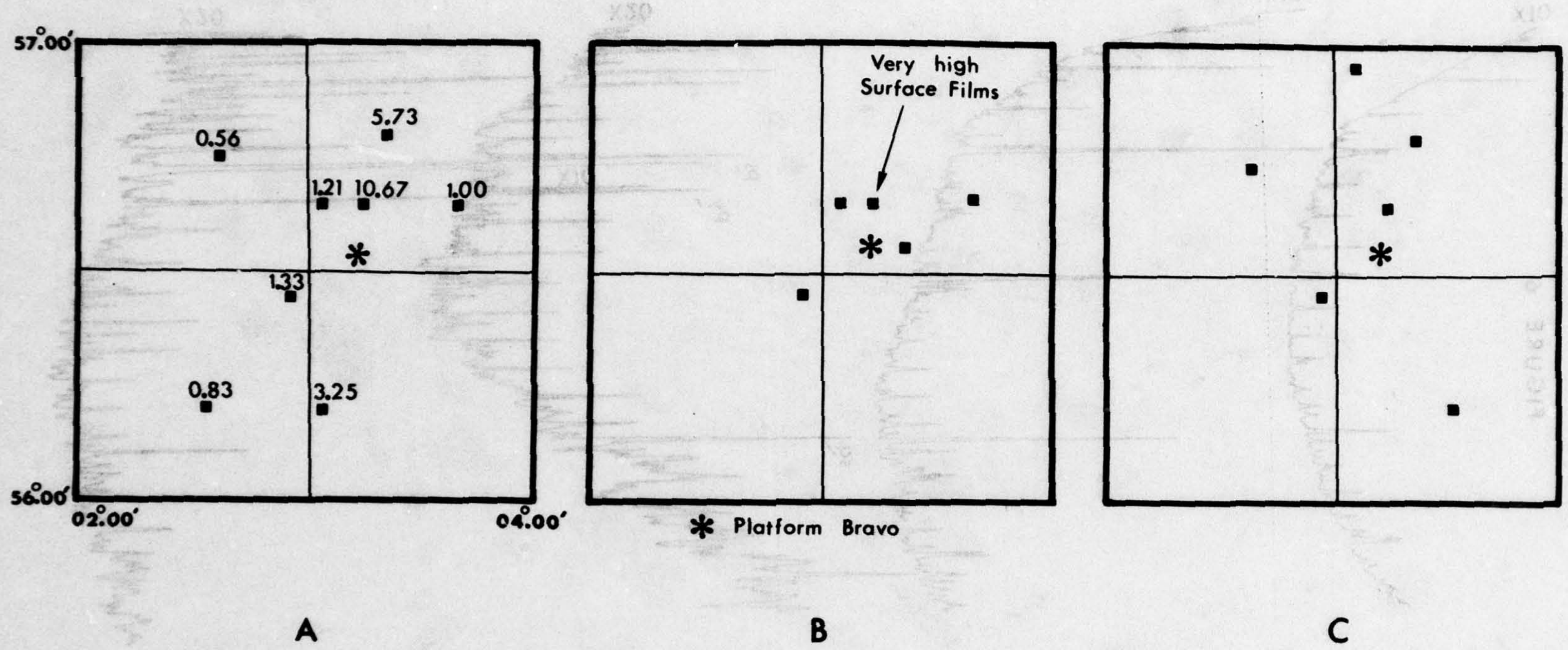
FIGURE 4

Comparison of haddock gut analyses with alkanes C_{13}-C_{19} from Ekofisk crude



A - Sample E1; B - Sample E6; C - Ekofisk crude; pi - pristane; py - phytane

FIGURE 5. Mussel phytane/n-C_{18} ratios, sea water fluorescence, tar ball and surface film values compared.

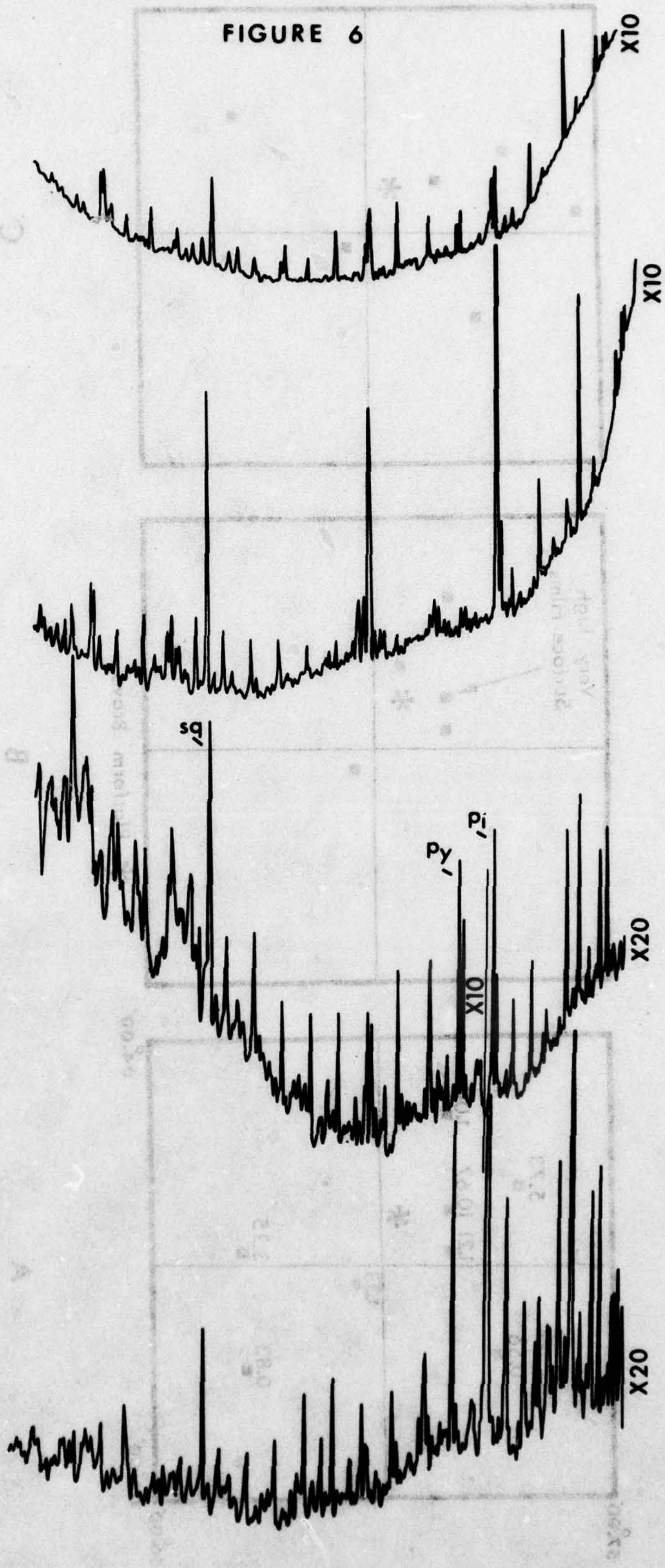


Mussel phytane/n-C_{18} ratios.

Sea water fluorescence, >1µg/litre.
Surface film, 88-264 g/metre^2.

Surface tar, >0.1mg/metre^2

FIGURE 6. Chromatograms of mussel alkane analyses.



A - Initial control; B - G7; C - G23; D - Final Control; pi - pristane; py - phytane; sq - squalane (internal standard)

TABLE 1

Fishery statistics for the North Sea and the area around Ekofisk*

	NORTH SEA (area defined by ICES)				
1973	Total nominal catch, fish and shellfish, all countries				3.2×10^6 tonnes
	Approximate total value (based on Scottish first sale prices)				£ 400 $\times 10^6$
	Pelagic catch :	U.K.	109.9×10^3 tonnes	Total	1186.7×10^3 tonnes
	value:		£ 5.5×10^6		£ 59.7×10^6
	Demersal catch :	U.K.	324.4×10^3 tonnes	Total	1789.8×10^3 tonnes
	value:		£ 53.2×10^6		£ 293.7×10^6
	Shellfish catch:	U.K.	31.5×10^3 tonnes	Total	228.0×10^3 tonnes
	value:		£ 10.4×10^6		£ 74.9×10^6
	NORTHERN NORTH SEA (above latitude 55°30'N)				
1971–1975	Approximate average annual demersal catch				1100 $\times 10^3$ tonnes
	EKOFISK AREA (box defined in Figure 1)				
1971–1975	Approximate average annual demersal catch				370 $\times 10^3$ tonnes

* Catch data from ICES Bulletin Statistique

TABLE 2

A Comparison of n-alkane* data from the Ekofisk May and July Sampling 1977 and the U.K. Survey 1971-1975

		Survey (open sea, range)	Ekofisk, May E1	E2	E3	E4	E6	Ekofisk, July G1	G3	G8
Mackerel (Scomber scombrus)	liver	1.3-6.3	0.4					3.5		
	muscle	0.6-1.4	0.4					0.8		
	gut		3.2					0.6		
	gonad		0.08							
	gills		0.3							
Plaice (Pleuronectes platessa)	liver	8.9	4.4		1.0	1.4	2.3			
	muscle	1.5	0.08		0.4	0.05	0.1			
	gut		0.7		0.1	0.4	0.4			
	gonad		1.0		2.1		0.4			
	gills				0.8	0.5	0.6			
Cod (Gadus morhua)	liver	1.4-4.6							1.0	1.7
	muscle	0.1-0.2							0.1	0.2
	gut								0.4	10.2
Haddock (Melanogrammus aeglefinus)	liver	2.8-3.9	0.4	0.6	0.8		0.5	0.85	1.1	2.6
	muscle	0.3-1.7	0.2	0.07	0.3	0.08	0.1	0.5	0.1	0.15
	gut		0.2	0.2	0.1	0.4	0.2	0.4	0.4	1.5
	gonad		1.3	1.0	0.5	0.6	0.2			
	gills		1.0	0.9	0.3	0.06	0.3			
Whiting (Merlangus merlangus)	liver	1.6-3.9						0.7		3.2
	muscle	0.2						0.1		0.15
	gut							0.5		1.7

* Total n-alkanes $C_{[illegible]}$ to $C_{[illegible]}$ µg/g wet weight

TABLE 3

Alkanes* in mussels (Mytilus edulis) kept in moored cages in the Ekofisk area, July 1977

Mussel sample/Station No	Initial Control	G4	G7	G8	G10	G21	G23	G34	G35	Final Control
n-Alkanes C_{15} to C_{33}	0.401	0.215	0.174	0.213	0.312	0.294	0.401	0.44	0.261	0.384
Pristane	0.031	0.026	0.112	0.052	0.039	0.106	0.085	0.282	0.114	0.415
Phytane	0.015	0.007	0.004	0.005	0.010	0.026	0.034	0.086	0.032	0.084
Pristane/Phytane ratio	2.07	3.71	28.0	10.4	3.9	4.08	2.5	47.0	3.56	4.94
Pristane/C_{17} ratio	0.86	1.86	7.47	2.0	1.77	4.24	2.13	11.75	11.4	207.5
Phytane/C_{18} ratio	0.68	1.0	1.33	0.83	0.56	3.25	1.21	5.73	10.67	6.46
Hours aboard ship before deployment		27	43	48	63	116	124	159	160	
Hours cage moored		96	54	46	120	96	65	59	59	
Order in which retrieved +		3	2	1	4	5	6	7	8	

* μg/g wet weight   + The cages were moored in sequence according to Station number

EFFECTS OF SPILLS ON WILDLIFE

Chairman: HARRY M. OHLENDORF
Patuxent Wildlife Research Center, USF&WS

BIOLOGICAL EFFECTS OF PETROLEUM ON AQUATIC BIRDS

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ABSTRACT

Studies at Patuxent Wildlife Research Center, U. S. Fish and Wildlife Service, have repeatedly demonstrated that microliter amounts of crude and refined oils applied to the surface of fertile eggs of various species of aquatic birds in laboratory and field studies result in high embryonic mortality that is both dose-dependent and developmental stage-sensitive. Some teratogenic effects occurred when oil applications were made during the first few days of incubation and these effects were enhanced by including metals found in petroleum. Alkane mixtures of hydrocarbons had virtually no embryotoxic effects. However, some aromatic hydrocarbon mixtures, especially those containing chrysene, were embryotoxic. 'Weathered' crude and refined oils were less toxic than fresh oil to embryos.

Oil ingestion affected egg production in adult mallards and growth of ducklings. Biochemical lesions were apparent in ducklings following oil ingestion but not so obvious in adults. However, elevated liver plasma clearance rates, evident in adults, suggest a compensatory response. Vanadium feeding studies showed altered lipid metabolism in laying hens but little accumulation in the eggs. From these studies we conclude that oil spills and oil pollution probably pose the greatest threat to the developmental and reproductive phases of the life cycle of aquatic birds.

INTRODUCTION

Disastrous oil spills, such as the recent spill by the tanker *Amoco Cadiz*, frequently destroy marine flora and fauna. One of the most notable single effects of such spills is the oiling of large numbers of marine birds. For example, as many as 30,000 birds died after the grounding of the tanker *Torrey Canyon* in 1967 (Bourne et al. 1967). Petroleum hydrocarbons are found in the highest concentrations in waters near shore, harbors, and river estuaries that are near heavy traffic routes of oil tankers (Wilson and Hunt 1975). Such areas are often used by breeding marine and wetland birds and oil has been often observed adhering to their plumage (Rittinghaus 1956; Birkhead et al 1973). The most immediate detrimental effect of oiling adult birds is feather matting which results in loss of bouyancy and insulation (Hartung 1967). Other effects that are equally detrimental include ingestion of oil by preening and through the food chain (Hartung and Hunt 1966; Hartung 1967).

Avian embryos are very sensitive to microliter quantities of crude and refined oil applied externally to the eggshell surface (Albers 1977; Szaro and Albers 1977; Szaro et al. 1978). Therefore small amounts of oil transferred from the plumage to eggs could be detrimental. In addition to oil spills, a continuous low level discharge of oil flows into the environment during normal usage of petroleum and birds have an ample opportunity for exposure at the chronic as well as the acute level. Investigations at Patuxent Wildlife Research Center (PWRC) have been

evaluating acute and chronic aspects of the biological effects of petroleum and its components on all stages of the life cycle of aquatic birds. The objectives of these studies have included the following assessments: (1) hatchability and embryonic development of eggs exposed to petroleum, (2) the development of ducklings fed oil from the time of hatching, and (3) physiological and reproductive effects of direct oil and food chain oil ingestion in adult waterfowl. The following overview includes references to our earlier studies (reviews by Dieter 1977; and Szaro 1977) as well as recent and ongoing studies at PWRC.

THE EFFECTS OF EGG OILING ON EMBRYONIC SURVIVAL AND HATCHING SUCCESS

Studies at PWRC have repeatedly demonstrated that only microliter amounts of various crude or refined oils applied to the surface of fertile eggs at different stages of incubation cause high embryonic mortality in many species of aquatic birds. As little as 5 µl of South Louisiana crude oil, Kuwait crude oil, or No. 2 fuel oil applied on the eighth day of incubation caused 76-98% mortality in mallards, (*Anas platyrhynchos*) (Table 1). Relatively large applications of an alkane mixture of compounds occurring in crude oil or of propylene glycol had virtually no effect on embryonic survival. Since the alkane (paraffin) mixture or propylene glycol coated as much or more surface area of the eggs as did the oil it was concluded that embryonic mortality was a result of toxicity rather than oxygen deprivation caused from coating shell pores. The toxicity of oil on embryos was clearly dependent on their age (Table 2). Application of 5µl of South Louisiana crude oil on the tenth day of incubation or earlier resulted in 92% or greater mortality; applications of No. 2 fuel oil resulted in 32-87% mortality. Treatment of eggs on or beyond day 14 resulted in considerably less mortality.

The embryotoxicity of oils was not confined to mallards. Eggs of eider (*Somateria mollisima*) of mixed incubation ages were collected from the Maine seacoast and were externally oiled with 20 µl of No. 2 fuel oil which resulted in 31% mortality (Table 3a). Significant mortality also occurred in nest-incubated eggs that were oiled (Table 3b). Eider eggs were not as sensitive as mallard eggs. However, two factors may account for this difference: (1) eider embryos are twice the size of mallard embryos requiring a different dose-weight relationship, and (2) the eider embryos treated were of mixed ages and therefore early age-dependent sensitivity would not be as evident. Eggs from 90 nests of great black-backed gulls (*Larus marinus*) on the Isles of Shoals, Maine, were treated with 5 µl and 20 µl of No. 2 fuel oil in their nests (Table 4). After 8 days, 40% of the clutches treated with 20 µl of oil per egg had survived, 80% of those treated with 5 µl had survived, and 89% of the controls were alive. Survival rates differed significantly between controls and the 20 µl group but not between controls and the 5 µl group. When the eggs of this species were incubated in the laboratory until the time of hatching, embryonic mortality was significantly greater in both oil groups than in controls (Coon et al. 1978). The mean embryonic age at treatment of these eggs was estimated to be 12 days and was based on the back calculated age of control eggs that hatched. It is probable that treatment at an earlier age of development would have had an even more detrimental effect.

Similar field studies were conducted with No. 2 fuel oil on eggs of Louisiana heron (Hydranassa tricolor), laughing gull (Larus atricilla), and sandwich tern (Sterna sandvicensis) located on Sundown Island in Matagorda Bay, Texas, one of the largest breeding colonies on the Texas coast (White et al. 1978). Each oil-treatment group and control group consisted of 60 eggs. Each egg in the oil-treatment group received 20 µl and was allowed to remain in the nest for 5 days after treatment before removal. Mortalities ranged from 56 to 83% after oil treatment; mortalities were highest in laughing gulls. Mortalities in Louisiana herons and sandwich terns were similar in response. When the eggs of these species were incubated in the laboratory, reductions in hatching occurred.

Other egg oiling studies have dealt with the effects of weathered oil. Prudhoe Bay crude oil and No. 2 fuel oil were weathered outdoors for 4 weeks and oil samples were collected weekly (Szaro et al. 1978). Mallard eggs were treated at 8 days of incubation with 1 to 50 µl of oil. Seven days of weathering caused no alteration in the toxicity of either oil, but 14 days of weathering decreased the toxicity of No. 2. fuel oil as reflected by an overall increase in hatchability. Weathering had no effect on toxicity of Prudhoe Bay crude oil until after 21 days when hatchability increased significantly. Amelioration of the embryotoxicity of both oils by weathering increased the hatchablity by at least twofold compared with fresh oil.

EMBRYOTOXIC AND TERATOGENIC EFFECTS OF PETROLEUM AND AROMATIC HYDROCARBONS

In other studies we examined the teratogenic potential and temporal pattern of mortality of crude oil and different aromatic hydrocarbon components. External application of South Louisiana crude oil on eggs of mallards at 24 hours of development caused little mortality (determined by daily candling of eggs) until the fourth and fifth days of development (Figure 1). At this time there was a rapid decline in survival and by 6 days of incubation over half of all mortality for that dose level had occurred. A second major decline in survival occurred after day 7 and through day 10 of development; further mortality was slight after 13 days development. Treatment of eggs at 72 hours of development produced a somewhat more dramatic decline in survival after day 7 and through day 10 (Hoffman 1978a, 1978b). The second period of major mortality (days 8 through 10) occurred just after the time of rapid outgrowth of the chorio-allantoic membrane over the surface of the inner shell membrane, suggesting increased potential for rapid uptake of oil components by this membrane. Embryos that survived to day 18 were examined for external, soft tissue, and skeletal defects (Table 5). Embryonic weights were significantly lower in the oil treated groups than in the paraffin (alkane) treated and untreated controls. The crown-rump length was significantly shorter in the 5µl oil group but not in the 1 µl oil group. The bill length was significantly shorter in both the 1 µl and 5 µl oil groups. The percentage of survivors that were abnormal ranged from 29 to 63%. However, to produce abnormal survivors a relatively high incidence of mortality was required.

Treatment at 24 hours of development with 1 µl of crude oil (Table 5)

produced a significant number of abnormal survivors at 18 days. The most common abnormalities included deformed bills (generally with a reduced upper bill), incomplete ossification of the phalanges, reduction in the size of liver lobes, and general stunting. Single cases of reduction in the number of ribs, and abnormal cervical vertebrae and spina bifida occurred.

Since surface application of alkane compounds occurring in crude oil (paraffin mixture) had virtually no embryotoxic effects, it was concluded that aromatic hydrocarbons in petroleum were probably responsible for the toxicity. Furthermore, kerosene, which is relatively low in aromatic hydrocarbon content, was not highly toxic (Hoffman, unpublished data). Therefore, other studies were conducted to assess the effects of single aromatic compounds and mixtures occurring in crude oil. Mallard eggs were exposed at 72 hours of development to 20 µl of a mixture of aromatic hydrocarbons or to 20 µl of the individual classes comprising the mixture (Table 6). The class composition of the mixture was generally based on that of South Louisiana crude oil. Application of 20 µl of the aromatic mixture reduced survival to 42%. The temporal pattern of mortality was similar to that of South Louisiana crude oil; however, the mixture was not as toxic as crude oil. The mean embryonic weight, crown-rump length, and bill length at 18 days were significantly less than in the control group or the paraffin treated group. The number of survivors that were abnormal was significantly greater after treatment with the aromatic mixture compared to paraffin. Of the individual classes of aromatic hydrocarbons tested, tetracyclics (pyrene) caused some mortality but other classes had virtually no effect on survival; the percentage of abnormal survivors did not differ significantly from the controls. It was therefore concluded that the embryotoxicity caused by the aromatic mixture was probably of a synergistic nature among classes. Classes were tested in all possible combinations of two (Hoffman, unpublished data). Combinations containing the tetracyclic aromatic hydrocarbon pyrene as well as a combination of thiopheno and dicyclic aromatic hydrocarbons resulted in low levels of mortality. However, no combination of two classes appeared to produce the effect of the entire mixture. Additional studies are underway to determine the effects of other tetracyclic and polycyclic aromatic compounds. The tetracyclic aromatic hydrocarbon chrysene has been reported to be as high as 0.2% in Kuwait crude oil (Pancirov 1974) and 0.5% in South Louisiana crude oil (Lawler, personal communication). Addition of 0.5% chrysene to the above aromatic mixture even at half of its concentration (26% aromatic mixture (w/w)) resulted in considerable enhancement of embryotoxicity (Table 7). It is possible that the presence of additional unidentified tetracyclic and higher polycyclic aromatic compounds could enhance the toxicity even further.

PHYSIOLOGICAL AND REPRODUCTIVE EFFECTS OF PETROLEUM AND AROMATIC HYDROCARBON INGESTION

Hens from paired mallards fed 2.5% South Louisiana crude oil laid fewer eggs than pairs fed 0.25%, a mixture of 1% paraffins or untreated control pairs; egg production for 30 days dropped from an average of

25 eggs/hen in the untreated group to 11 eggs/hen in those fed 2.5% crude oil (Coon, upublished data). Our contract investigator has reported similar results with mallards fed 1%, 3%, or 5% South Louisiana crude oil (W. Holmes, U. Cal., Santa Barbara, personal communication).

Duckling growth was impaired when a diet containing 5% South Louisiana crude oil was ingested from hatching until 8 weeks of age (Szaro 1977; Szaro et al 1978). In these ducks, as well as those fed 2.5% South Louisiana crude oil, flight feathers failed to develop normally and liver hypertrophy and splenic atrophy were evident. Biochemical lesions occurred and included elevations in activities of the plasma enzymes alanine aminotransferase and ornithine carbamyl transferase which are indicative of liver and kidney damage. Measurements of the accumulation of petroleum hydrocarbons in the tissues of these ducks were done by high-resolution gas chromatography and mass spectrometry (Lawler et al 1978a, 1978b).

Enzyme activities in adults fed diets containing up to 2.5% South Louisiana crude oil or representative aromatic hydrocarbons of that oil did not reveal the same biochemical lesions found in ducklings fed the oil. Indocyanine green dye, a compound that is metabolized entirely by the liver, was used to measure liver function in mallard drakes fed representative aromatic hydrocarbons (Table 8). The ingestion of 4000 ppm aromatic mixture caused a significant elevation of the liver plasma clearance rates which suggests that adult waterfowl may be able to eliminate higher concentrations of petroleum hydrocarbons than ducklings.

Additional studies have dealt with the effects of feeding waterfowl various invertebrates that had been exposed to petroleum hydrocarbons to determine the extent of accumulation in their tissues. Crayfish are readily accepted by mallards as food and radio-labelled aromatic compounds are being used as tracers to follow the oil through the food chain. Radioactive napthalene was readily taken up by the crayfish and ducks that were fed the crayfish accumulated most of the label in their gall bladders followed by accumulation in fat, kidney, liver, and blood (Tarshis, unpublished data).

TOXIC EFFECTS OF METAL COMPONENTS FOUND IN PETROLEUM

Some crude oils contain high concentrations of nickel and vanadium, and concentrations of vanadium in Venezuelan crude oils have been reported as high as 1400 ppm (Committee on Biologic Effects of Atmospheric Pollutants, 1974). Vanadyl porphyrin or nickel porphyrin was added to South Louisiana crude oil to produce a metal concentration of approximately 700 ppm. The content of these metals in South Louisiana crude oil is only several ppm so that this experiment provided an opportunity to compare the toxicity of crude oil with and without these metals and in a molecular form (porphyrin) occurring naturally in crude oil (Yen 1975). Mallard embryos of 72 hours were treated with 1 µl of the crude oil, 1 µl of crude oil containing vandium, or 1 µl of crude oil containing nickel by external egg application. Survival rates of all three treatment groups were significantly reduced by about 50% compared with untreated controls (Table 9). Survival rates among crude oil, vanadium, and nickel treatment groups did not differ significantly

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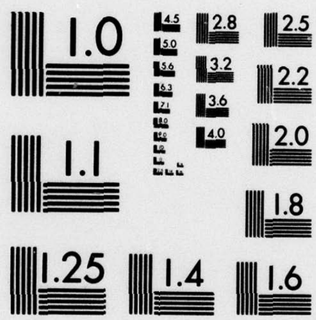

MICROCOPY RESOLUTION TEST CHART
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at this dose level. However, the presence of nickel or vanadium resulted in significantly lower mean embryonic weights at 18 days of development compared with treatment with 1 µl of crude oil alone. Mean crown-rump lengths were significantly shorter in all three treatment groups. Mean bill lengths were significantly shorter in all three treatment groups, but the effects of vanadium or nickel were significantly greater than in crude oil alone. A more pronounced effect of these metals was an increased frequency of overtly abnormal surviving embryos at 18 days of development compared with those treated with crude oil alone. These abnormalities included bill and eye defects and hydrocephalus as well as general stunting.

Mercury occurs in most crude oils at much lower concentrations than vanadium and nickel; some crude oils have been reported to contain as high as 30 ppm and 72 ppm of mercury (Alshahristani and Alattiya 1973; Yen 1975). Mercury also occurs in the organic form in crude oil (Yen 1975). An organic form of mercury (CH_3HgCl) was dissolved into a non-toxic paraffin mixture with 10% ethyl acetate and externally applied to eggs (Table 10). Relatively high amounts of mercury were required to significantly affect survival, embryonic weight, or crown-rump length. However, much lower amounts caused overt defects of the eye, brain, bill, and limbs.

Feeding studies were conducted to determine the extent of vanadium accumulation in eggs, blood, brain, fat, liver, kidney, and bone (femur) of mallard ducks and to examine the effects of vanadium on lipid metabolism (White and Dieter 1978). Ducks were fed ad libitum with commercial duck breeder mash coated with either 1, 10, or 100 ppm (wet weight) vanadyl sulfate dissolved in propylene glycol for 12 weeks. Vanadium accumulated to higher concentrations in the bone and liver than in other tissues (Table 11). Concentrations in bones of hens were five times those in bones of drakes, suggesting an interaction between vanadium and calcium mobilization in laying hens. Very little vanadium accumulated in eggs of laying hens. Triglyceride/cholesterol ratios indicate lipid metabolism was altered in laying hens fed 100 ppm vanadium by 3 weeks of treatment and fed 10 ppm by 12 weeks of treatment (White and Dieter 1978).

SUMMARY AND CONCLUSIONS

Investigations at PWRC have evaluated certain acute and chronic aspects of the biological impact of petroleum and its components in aquatic birds. These studies included assessments of embryonic development and hatching success of eggs externally exposed to petroleum and its components, and the effect of oil ingestion on the development of ducklings and on adult reproduction and physiology. Microliter applications of crude or refined oil on the surface of fertile eggs of mallards, common eiders, great black-backed gulls, sandwich terns, Louisiana herons, and laughing gulls were embryotoxic under both laboratory and field incubation conditions. Other manifestations of embryotoxicity included some teratogenic effects when oil application was made during the first few days of development. Teratogencity was further increased when the oil was supplemented with metals occurring in petroleum including vanadium,

nickel, and mercury. Mixtures of alkane hydrocarbons occurring in oil had virtually no embryotoxic effects suggesting that aromatic hydrocarbons were the embryotoxic component. Studies with mallard embryos to evaluate major classes of aromatic hydrocarbons in crude oil revealed that synergism among classes as well as the presence of the tetracyclic aromatic chrysene were contributing factors for embryotoxicity. 'Weathered' crude oil (Prudhoe Bay crude) and refined oil (No. 2 fuel oil) were less embryotoxic indicating that a fresh oil spill would have the most deleterious effects on embryonic survival. All of these findings indicate the detrimental potential of the transfer of minute amounts of oil from the plumage of oiled birds to their eggs. Oil ingestion decreased egg production in mallards as well as growth in ducklings. Biochemical lesions, indicative of liver and kidney damage, were apparent in the ducklings after oil ingestion but were not so obvious in adults. However, elevated liver plasma clearance rates were apparent in adults, suggesting a compensatory response. Other studies with vanadium, which occurs in high concentrations in some crude oils, showed high accumulation of the metal in the bones and liver of adult mallards and altered lipid metabolism in laying hens. These findings suggest that adult aquatic birds are generally able to tolerate or eliminate higher concentrations of petroleum and its components than are embryos and ducklings. Therefore, oil spills and oil pollution probably pose the greatest threat to developmental and reproductive phases of the life cycle of aquatic birds.

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Table 1.

Effects on hatching of mallard egg oiling[a] with different petroleum products (N=50)

Treatment[a]	Percent Mortality after Treatment with: South La. crude oil	Kuwait crude oil	No. 2 fuel oil
None	8	8	12
Propylene glycol (50 μl)	6	-	-
Alkane[b] mixture (50 μl)	4	-	-
Oil (1 μl)	38[c]	28[c]	36[c]
Oil (5 μl)	98[c]	76[c]	82[c]
Oil (10 μl)	98[c]	84[c]	90[c]
Oil (20 μl)	100[c]	94[c]	100[c]

Note: Data derived from Szaro et al. (1978).

a Fertile mallard eggs treated externally at day 8 of development.

b Mixed in equal proportions (w/w): pentadecane, hexadecane, heptadecane, octadecane, nonadecane, 2,2,4,6,6,-pentamethylheptane, 2,2,4,4,6,8,8-heptamethylnonane, 2,6,10,14-tetramethylpentadecane, decahydronapthalene.

c Significantly different from controls, P < 0.01, chi-square test.

Table 2.

Effects on hatching of 5 µl of oil on mallard eggs at different developmental stages (N=50)

Age of treated embryos (days)	Percent mortality after treatment with: South Lousiana crude oil	No. 2 fuel oil
Controls[a]	0	20
2	100[b]	87[c]
6	97[b]	67[c]
10	92[b]	32[c]
14	22[b]	17
18	12[b]	20
22	5	7

Note: Data derived from Albers (1978).

[a] Mortality of untreated control eggs checked by candling at each interval.

[b] Significantly different from controls, $P < 0.05$, binomial test.

[c] Significantly different from controls, $P < 0.05$, chi-square test.

Table 3.

(a) Effects on hatching of No. 2 fuel oil on common eider eggs of mixed ages incubated in the laboratory (N=48).

Treatment	Percent Mortality
None	4
Propylene glycol (50 µl)	4
Oil (5 µl)	8
Oil (20 µl)	31[a]

Note: Data derived from Szaro and Albers (1977).

[a] Significantly different from controls, $P < 0.01$, chi-square test.

(b) Effect on survival of No. 2 fuel oil on common eider eggs incubated in the nest for 7 days.

					Percent of clutch alive	
Treatment	Nests[a]	No. of eggs	Percent alive	Mean clutch size	Mean of[b] transformed percentages	Mean[c] percent
Control	13	60	98	4.6	75.42	93.7
No. 2 fuel oil (5 µl)	19	84	94	4.4	72.54	91.0
No. 2 fuel oil (20 µl)	16	72	74	4.5	59.40	74.1

Note: Data derived from Albers and Szaro (1978).

[a]3 nests were not found; 9 nests were abandoned or destroyed by predation. [b]Arcsine transformation for binomial proportions; angle = arcsine $\sqrt{\text{percentage}}$. Significant one-way analysis of variance, $P \leq 0.05$; 20 ul group significantly different from control group, t-test, $P \leq 0.025$. [c]Mean of transformed percentages converted back to percent.

Table 4.

Embryo survival in naturally-incubated great black-backed gull eggs 8 days after treatment with No. 2 fuel oil.

Treatment	No. of clutches	Survival Index	No. of eggs	Condition of embryo: Alive	Condition of embryo: Dead	Percent alive
Control	28	95.8	81	72	9	88.9
No. 2 fuel oil (5 µl)	26	90.3	72	58	14	80.6
No. 2 fuel oil (20 µl)	25	32.7[a]	72	29	43	40.3

Note: Data derived from Coon et al. (1978).

Most clutches contained three eggs; however, some contained only two at the time of treatment. For each clutch, a percentage of the total embryos alive 8 days after treatment was computed. Clutch survival data were evaluated statistically after angular transformation, arcsin $\sqrt{X}$. This transformation is applicable to binomial data expressed as percentages and covering a wide range of values (Steel and Torrie, 1960). The Survival Index reported can be described by the following expression $(\sin(1/n \sum \arcsin \sqrt{\%}))^2$ and is a transformation back to the original scale. Statistical comparisons were made on the transformed scale, rather than on the reported values.

[a] Significantly different from control, P < 0.05 (Student's t test).

Table 5.

Embryotoxic effects of South Louisiana crude oil on mallard eggs on day 1 of development (N=70).

Treatment	Percent survival	Embryonic weight (g)	Crown-rump length (mm)	Bill length (mm)	Percent abnormal survivors
Control	98.5	16.6 ± 1.73[a]	87.0 ± 3.38	13.7 ± 0.54	3
Paraffin[b]	100	16.8 ± 2.28	87.9 ± 3.93	13.6 ± 0.45	1.5
1 µl crude oil	57[c]	15.4[d] ± 2.62	85.4 ± 4.90	13.1[d] ± 0.74	29.4[c]
5 µl crude oil	17[c]	13.7[d] ± 4.13	82.4 ± 6.54	12.6[d] ± 1.04	63.6[c]
10 µl crude oil	1.4[c]	(7.7)	(69.5)	(9.5)	--

a Mean ± S.D.

b Composition of paraffin mixture was the same as that in Table 1.

c Significantly different from control and paraffin-treated groups, P < 0.01, chi-square test.

d Significantly different from control and paraffin-treated groups by one-way analyses of variance (P < .01) and Duncan's multiple range test (P < .05).

Table 6.

Embryotoxic effects of aromatic hydrocarbons on mallard eggs on day 3 of development (N=50).

Treatment	Percent survival through day 18	Weight (g)	Crown-rump length (mm)	Bill length (mm)	Percent abnormal survivors
Control	98	16.6 ± 1.73[a]	87.0 ± 3.38	13.7 ± 0.54	4
Paraffin[b] (20 μl)	98	16.3 ± 1.57	87.4 ± 3.51	13.8 ± 0.49	2
Aromatic mixture[c] (20 μl)	42[d]	14.5[e] ± 1.94	83.7 ± 2.11	12.6[e] ± 0.85	18[d]
Monocyclic (20 μl)	98	15.8 ± 1.69	84.5 ± 4.19	12.6[e] ± 0.85	4
Dicyclic (20 μl)	96	16.4 ± 1.68	85.8 ± 3.53	12.9 ± 0.84	2
Tricyclic (20 μl)	98	16.5 ± 1.44	87.2 ± 2.68	12.9 ± 0.51	2
Tetracyclic (20 μl)	86[d]	15.9 ± 1.83	85.5 ± 3.28	13.3 ± 0.60	6
Heterocyclic (20 μl)	100	16.4 ± 1.47	84.4 ± 3.52	12.7 ± 0.45	2
Thiopheno (20 μl)	96	16.0 ± 1.49	87.1 ± 3.34	12.6[e] ± 0.63	6

[a] Means ± S.D.

[b] The composition of the paraffin mixture was the same as that in Table 1.

[c] The aromatic mixture was 52% aromatic hydrocarbons and 48% paraffin mixture by weight and consisted of the following composition by weight: monocyclic aromatics (20%) including ethylbenzene, pentamethylbenzene, 1-phenylhexane, 1-phenyltridecane, and tetralin at 4% each; dicyclic aromatics (20%) -dimethylnaphthalene, acenapthalene, acenaphthene, dibenzofuran, and fluorene at 4% each; tricyclic aromatics (3%) -phenanthrene; tetracyclic aromatics (1%) - pyrene; thiopheno aromatics (3%) - benzothiophene, and dibenzothiophene at 1.5% each; other heterocyclic aromatics (5%) -2,3,3, - trimethylindolenine. Individual classes of aromatics tested were at the same concentration as found in the aromatic mixture, and were mixed with the paraffin.

[d] Significantly different from control and paraffin treated groups by chi-square.

[e] Significantly different from control and paraffin treated groups by one way analysis of variance ($P < .01$) and Duncan's multiple range test ($P < .05$).

Table 7.

Embryotoxic effects of external application of aromatic hydrocarbons containing chrysene on mallard eggs on day 3 of development (N=80).

Treatment	Percent survival through day 18	Weight (g)	Crown-rump length (mm)	Bill length (mm)	Percent abnormal survivors
Controls	98	14.9 ± 1.46^{a}	84.9 ± 3.19	13.0 ± 0.61	6.5
Aromatic[b] mixture (10 μl)	87^{c}	15.2 ± 1.24	83.0 ± 4.44	$12.1^{d} \pm 0.70$	10.5
Aromatic mixture + 0.5% chrysene (10 μl)	41^{c}	$13.2^{d} \pm 1.42$	$78.6^{d} \pm 4.00$	$11.0^{d} \pm 0.75$	37.5^{c}

a Mean ± S.D.

b The composition of the aromatic mixture was 26% aromatics by weight and 74% paraffin and included all components in Table 6 but at half that concentration.

c Significantly different from the control group, P < .01, chi-square test.

d Significantly different from the control group by one way analysis of variance (P < .01) and Duncan's multiple range test (P < .05).

Table 8.

Liver function in mallard drakes fed hydrocarbon mixtures[a] representative of those in South Louisiana crude oil (N=12).

Treatment	Plasma clearance rate (ml/min/kg body weight) Pretreatment	Months 1	3	5
Control	13.7 ± 1.1[b]	13.5 ± 0.8	13.5 ± 0.7	13.1 ± 0.7
Alkane mix, 10,000 ppm	14.0 ± 1.1	14.7 ± 0.7	14.9 ± 0.7	13.1 ± 0.7
Aromatic mix, 400 ppm	13.4 ± 1.0	15.5 ± 0.8	15.2 ± 0.7	14.7 ± 0.5
Aromatic mix, 4000 ppm	14.1 ± 1.0	17.0[c] ± 1.4	18.5[c] ± 1.0	18.5[c] ± 1.2

Note: Data derived from Patton (Dieter 1977).

[a] The aromatic mixture consists of an equimolar ratio of 10 compounds (ethyl benzene, 1,2,3,4-tetrahydronaphthalene, dimethylnaphthalene, 2, 3-trimethylindolenine, acenaphthylene, acenaphthene, phenanthrene, 2-methylbenzothiazole, dibenzothiophene, and 2,6-dimethylquinoline) dissolved in 1% alkanes (equimolar mixture of tridecane, pentadecane, hexadecane, heptadecane, octadecane, nonadecane, 2,2,4,6,6-pentamethyl heptane, 2,2,4, 4,6,8,8-heptamethylnonane, 2,6,10,14-tetramethylpentadecane, and decahydronaphthalene) in the feed.

[b] Mean ± S.E.

[c] Significantly different from controls, P 0.05, one-way analysis of variance and Duncan's multiple range test.

Table 9.

Effects of adding vanadium or nickel to South Louisiana crude oil applied to mallard eggs on day 3 of development (N=70).

Treatment	Percent survival (through day 18)	Embryonic weight (g)	Crown-Rump length (mm)	Bill length (mm)	Percent abnormal survivors
Control	97	14.4 $\pm$ 1.12[a]	85.6 $\pm$ 3.57	13.3 $\pm$ 0.80	1.5
1 µl crude oil	54[b]	14.3 $\pm$ 1.96	81.7[c] $\pm$ 5.93	12.5[c] $\pm$ 1.02	10.7[b]
1 µl crude oil & vanadium (700 ppm)	47[b]	12.9[c] $\pm$ 2.52	79.7[c] $\pm$ 5.77	11.6[c] $\pm$ 1.23	36.0[b]
1 µl crude oil & nickel (700 ppm)	44[b]	13.0[c] $\pm$ 1.74	80.3[c] $\pm$ 3.38	11.8[c] $\pm$ 1.33	44.0[b]

[a] Mean $\pm$ S.D.

[b] Significantly different from control group, P < .01, chi-square test.

[c] Significantly different from control group by one-way analysis of variance (P < .01) and Duncan's multiple range test (P < .05).

Table 10.

Effects of paraffin containing mercury on mallard eggs on day 3 of development (N=80).

Treatment	Percent survival (through day 18)	Embryonic weight (g)	Crown-rump length (mm)	Bill length (mm)	Percent abnormal survivors
Control	97	16.7 ± 1.38[a]	87.9 ± 3.03	13.5 ± 0.56	1.3
Paraffin[b]	96	16.7 ± 1.79	87.8 ± 3.73	13.3 ± 0.59	2.6
CH_3HgCl (μg of Hg)					
3.0	97	16.4 ± 1.44	88.1 ± 3.39	13.0[c] ± 0.50	11.5[d]
9.0	88[d]	16.2 ± 1.62	87.6 ± 3.65	13.4 ± 0.53	11.4[d]
27.0	63[d]	16.0[c] ± 2.28	83.5[c] ± 6.31	13.2[c] ± 0.73	30.0[d]
90.0	49[d]	14.6[c] ± 2.01	83.1[c] ± 4.78	12.8[c] ± 0.57	28.2[d]

a Mean ± S.D.

b The paraffin mixture contained 10% ethyl acetate but otherwise was the same as that in Table 1.

c Significantly different from controls by one-way analysis of variance (P < .01) and Duncan's multiple range test (P < .05)

d Significantly different from the control group, P < .01, chi-square test.

Table 11.

Tissue accumulation of vanadium fed to mallard ducks in the diet.

Vanadium[b] added to diet (ppm)	Tissue vanadium residues (ppb, wet weight)[a]				
	Brain	Fat	Kidney	Liver	Femur
0	0.5 ± 0.1	2 ± 1	1 ± 0.3	19 ± 5	100 ± 22
1	0.8 ± 0.2	3 ± 2	3 ± 0.7	17 ± 4	92 ± 15
10	0.5 ± 0.2	11 ± 7	18 ± 2.0	61 ± 20	251 ± 80
100	9.0 ± 1.0	20 ± 11	273 ± 49.0	657 ± 113	274 ± 47 (male) 3327 ± 2208 (female)

Note: Data derived from White and Dieter (1978).

[a] Mean ± SE; n=5 pairs per treatment.

[b] In the form of vanadyl sulfate.

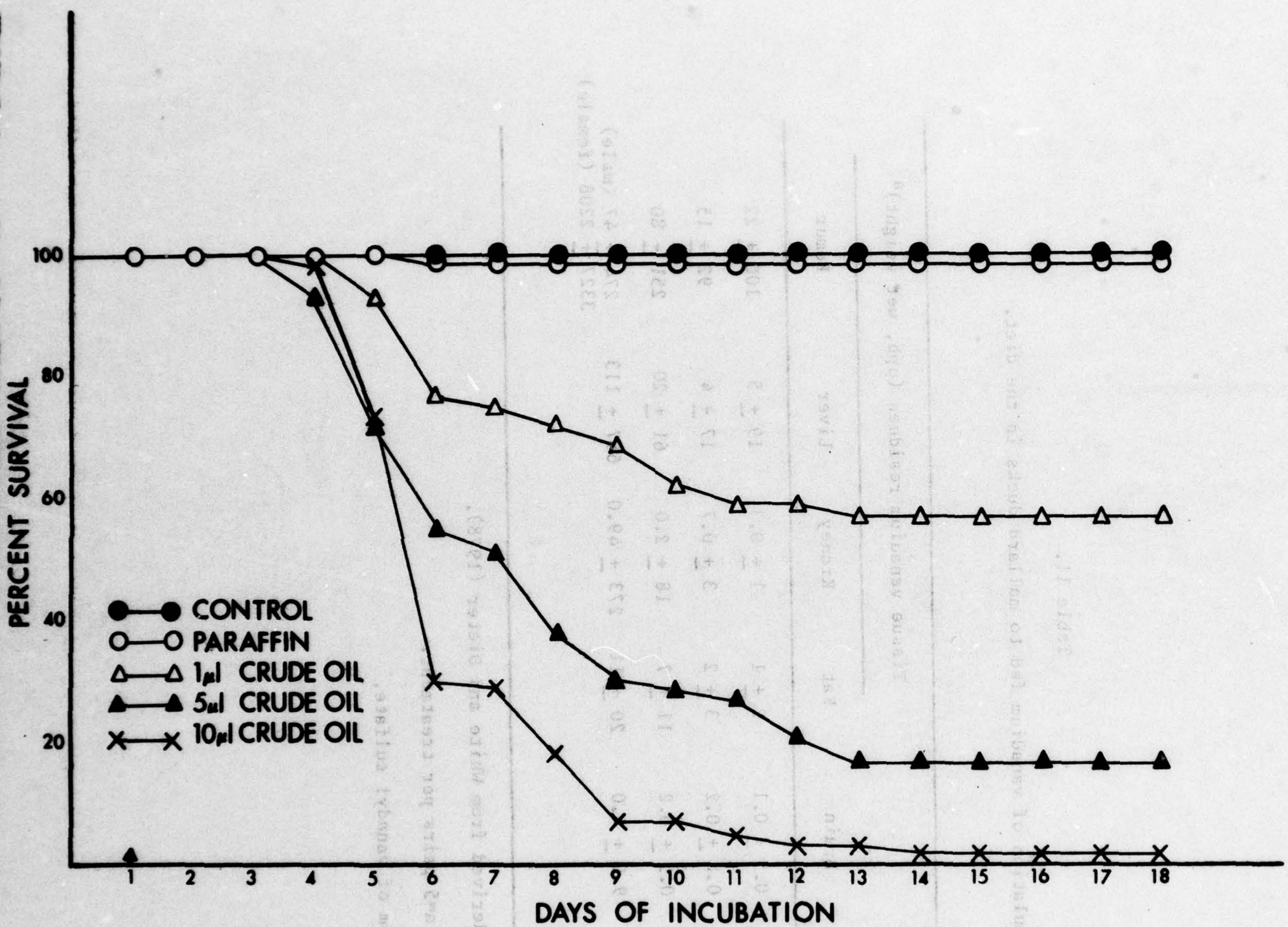

Figure 1. Effects of South Louisiana crude oil on survival of mallard embryos. ▲ (The oil was applied on day 1 of development).

QUANTIFICATION OF PETROLEUM HYDROCARBONS IN SELECTED TISSUES OF MALE MALLARD DUCKLINGS CHRONICALLY EXPOSED TO SOUTH LOUISIANA CRUDE OIL

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ABSTRACT

Heart, liver, and kidney tissues from male mallard ducklings that had ingested commercial duck starter containing 0.025%, 0.25%, 2.5%, and 5.0% South Louisiana crude oil from hatch to 8 weeks (Szaro et al. 1978) were analyzed for their oil hydrocarbon contents. Fifty-five specific saturated and aromatic oil hydrocarbons were quantitated. Total oil saturates, total oil aromatics, and total oil hydrocarbons were also determined for each tissue treatment group. Individual and total oil hydrocarbon concentrations relative to oil dosage are discussed in relation to the previously reported toxic responses of the ducklings.

INTRODUCTION

Increased world-wide demand for oil must lead to increased transportation, storage, and processing of petroleum and petroleum products. Normal discharges of petroleum effluents during these activities could, therefore, result in increased low-level oil pollution in the marine and estuarine environments (Dieter, 1976), both of which are inhabited or frequented by marine birds. Subtle sublethal toxic responses of these birds to chronic low-level oil exposure are potentially more harmful to marine bird populations than oil spills, which are generally high-impact short-duration phenomena.

As part of a concerted effort to determine the effects of chronic

low-level oil exposure on bird populations, we report in this paper the results of quantitative hydrocarbon analyses performed on selected tissues of male mallard ducklings that were chronically exposed to low levels of South Louisiana crude oil (SLC oil). Szaro et al. (1978) performed the original physiological experiment, which was designed to assess the effects of chronic oil ingestion on mallard ducklings during their first eight weeks of development. The livers, hearts, and kidneys from these same ducklings were analyzed primarily to determine if there was a relationship between the concentrations of petroleum hydrocarbons in the three experimental tissues and the pathological responses observed in the ducklings.

METHODS AND MATERIALS

Tissue Samples

The conditions under which the mallard ducklings (Anas platyrhynchos) were raised and fed commercial duck starter containing different concentrations of South Louisiana crude oil (SLC oil) (American Petroleum Institute Reference Oil III) are described elsewhere (Szaro et al. 1978). Briefly, 250 ducklings were divided into 10 groups of 25 each. Two groups of ducklings made up the control and two groups of ducklings were used for each of four treatment groups. The ducklings in the treatment groups received 0.025, 0.25, 2.5, and 5.0 percent (w/w) concentrations of oil in their feed for eight weeks. At the end of the experiment, heart, kidney, and liver tissues were dissected from the control and experimental male mallard ducklings at the Patuxent Wildlife Research Center and shipped to us at -78°C. The tissues were kept at -4°C until analyzed.

In this study a tissue treatment group is defined as all of a particular type of tissue at a given treatment group level. Each experimental tissue, therefore, had 4 tissue treatment groups plus a control. Replicate analyses of pooled samples from each tissue treatment group were carried out.

Analytical Procedures

The hydrocarbon analytical procedure used in this study was adapted for use with duckling tissues from the procedure developed by Warner (1976) for quantification of saturated and aromatic hydrocarbons in marine organisms.

Extraction and Fractionation. Approximately 30 g wet weight of tissue was digested in 15 g of 4N KOH at 90°C for three hours. The nonsaponifiable lipids were then extracted with glass-distilled diethyl ether. Total nonsaponifiable lipids were taken up in pentane and fractionated on a 30 cm x 1.0 cm glass column packed with 15 g of silica gel, which had been activated by heating overnight at 150°C. The saturated hydrocarbon fraction was eluted with 35 ml of pentane and the aromatic hydrocarbon fraction with 80 ml of 20% dichloromethane in pentane. Each fraction was reduced to 2-3 ml in a Buchi Rotavapor-R (Brinkman Instruments) set at 30°C. Concentration to approximately 150 μl was accomplished at 90°C in 4 ml evaporative

concentrators equipped with modified micro Snyder columns (Lab Glass Inc.). Twenty-five microliters of the internal standard solution (480 ng of decalin per μl of benzene) were added after the samples were transferred to 200 μl cone-bottomed injection vials that had been calibrated to volumes of 200 μl and 50 μl. The final volume of each sample was adjusted to 200 μl by the addition of pentane before injection into a gas chromatograph. Some of the samples from the lower concentration treatment groups were injected from 50 μl volumes. Spectroquality solvents (Burdick and Jackson Laboratories) were used throughout this study.

Gas Chromatography. Gas chromatographic analyses were carried out on two Hewlett-Packard (H-P) model 5711A gas chromatographs. Each instrument was equipped with an H-P model 18740A glass capillary inlet system. One of the gas chromatographs also had an H-P model 7671A automatic liquid sampler. The signals from the hydrogen flame ionization detectors on each instrument were integrated by an H-P model 3354A data system. Systems integration methods were used for most analyses, but a special computer program (Overton et al. 1978), designed to obtain accurate peak integration in the presence of a large unresolved complex hydrocarbon mixture (UCHM), was used to integrate the liver saturate fraction gas chromatograms. Operation of the automated gas chromatographic system was described elsewhere (Lawler et al. 1978a).

Thirty meter by 0.4 mm ID glass capillary columns prepared and coated with SE-52 (Applied Science, Inc.) in the manner described by Grob and Grob (1976) were used for the analysis of both saturated and aromatic hydrocarbons. In each case, helium was the carrier gas and the flow rate was 2.5 ml per minute at 50°C. The ovens of the gas chromatograms were temperature programmed from 50 to 250°C at 2°C per minute, after an initial hold of four minutes. The hydrocarbons selected for quantification had previously been identified by us in SLC oil and in the tissues of SLC oil-exposed adult mallard ducks by combined gas chromatography and mass spectrometry (Lawler et al. 1978b; Lawler et al. 1978c). In this study, retention times were used to identify these same hydrocarbons in mallard duckling tissues.

Tests. The entire analytical procedure was tested for reproducibility and linearity over the expected concentration range of 10 parts per billion (ppb) to 400 ppb before any experimental tissues were analyzed. Reproducibility of the percent recovery data listed in Table 1 was used as a measure of the reproducibility of the analytical procedure. Four replicate analyses of 30 g breast muscle samples spiked with the equivalent of 50 ppb of each of the hydrocarbons in the recovery standard were run to determine the percent recoveries of the standard hydrocarbons. Reproducibility of the saturated hydrocarbon analysis was very good, as indicated by a mean coefficient of variation for the saturated hydrocarbon percent recovery data of 4.2%. The mean coefficient of variation for the aromatic hydrocarbon analysis was 17.2%. Data from analyses of 30 g breast muscle samples spiked with the equivalents of 10, 25, 50,

100, 200, and 400 ppb of each of the hydrocarbons in the recovery standard indicated that the analytical procedure was linear over the expected concentration range.

In this study fifty-five saturated and aromatic hydrocarbons were individually quantitated. Percent recoveries and relative response factors for the compounds for which authentic standards were not available were estimated from data obtained from analyses of the saturated and aromatic hydrocarbon standards.

Total Resolved Saturated and Total Resolved Aromatic Oil Hydrocarbons. Total resolved saturated and total resolved aromatic oil hydrocarbons were calculated for the three experimental tissues by the same procedure. In each case, the mean control concentration of each of the individually measured hydrocarbons was subtracted from the mean concentration of that hydrocarbon detected at each treatment group level. The adjusted concentrations of the individual saturated or aromatic hydrocarbons obtained for a particular tissue treatment group were then added and defined as total resolved saturated or total resolved aromatic oil hydrocarbons, depending upon the analysis. Nonacosane and hentriacontane were not included in the calculations of total resolved saturated oil hydrocarbons in the experimental tissues because they were detected in high concentrations in the duck's feed and assumed not to be of petroleum origin.

Total Saturated and Total Aromatic Oil Hydrocarbons. Total saturated and total aromatic oil hydrocarbons were determined for each tissue by a procedure that measured the concentrations of both the resolved hydrocarbons and the UCHM in each gas chromatogram. A computer program was designed to integrate all of the hydrocarbons eluting after the internal standard as a single peak. Areas of peaks obviously not of petroleum origin, such as nonacosane and hentriacontane in the saturate fractions and squalene in the aromatic fractions, were subtracted from the total areas of the gas chromatograms. These adjusted areas were then assigned the appropriate estimated relative response factor and used to calculate the concentration of total saturated or total aromatic oil hydrocarbons by an internal standard method of calculation. Mean control values were subtracted from mean experimental values to obtain the total saturated or total aromatic oil hydrocarbon concentrations in each tissue treatment group. The mean relative response factors for the saturated and aromatic hydrocarbon standards were used as the estimated relative response factors in the total saturated and total aromatic oil hydrocarbon calculations.

Total Oil Hydrocarbons. Total oil hydrocarbon concentrations for the tissues in each tissue treatment group were obtained by adding their total saturated and total aromatic oil hydrocarbon concentration values.

RESULTS

Quantification of Individual Hydrocarbons

The quantitative data acquired for the thirty-seven saturated and eighteen aromatic hydrocarbons analyzed in this study are presented in Figures 1-3 and Figures 4-6, respectively. The mean coefficients of variation for all of the saturated and all of the aromatic hydrocarbon measurements, excluding those measurements that fell below the 10 ppb lower limit of the tested concentration range, were calculated for the liver and heart analyses. The mean coefficient of variation for the saturated hydrocarbon measurements was 45% and for the aromatic hydrocarbon measurements it was 35%. These values, when compared to the mean coefficients of variation obtained for replicate analyses of the recovery standard saturated (4.2%) and aromatic (17.2%) hydrocarbons, give some indication of the variability introduced into the data by the addition of a biological factor to the system. These data underline the importance of doing replicate analyses of tissues utilized in low-level oil exposure experiments.

As an aid in visualizing differences between the relative concentrations of oil hydrocarbons detected in the tissues and those present in SLC oil, the concentrations of SLC oil hydrocarbons, expressed assuming no differential uptake or metabolism, were included in Figures 1-6. The SLC oil saturated hydrocarbon concentrations presented in Figures 1-3 were calculated by first equalizing the concentration of the C_{16}-isoprenoid alkane in SLC oil to the highest concentration of C_{16}-isoprenoid alkane detected in each particular tissue. The concentrations of the other saturated hydrocarbons in the SLC oil were then normalized to that of the C_{16}-isoprenoid alkane. The SLC oil aromatic hydrocarbon concentrations included in Figures 4-6 were calculated in the same manner. Naphthalene, however, was the compound against which the concentrations of the other SLC oil aromatics were normalized.

Saturated Hydrocarbons. Saturated hydrocarbons derived from SLC oil were detected in all three experimental tissues. Members of the isoprenoid alkane series and the *n*-alkylcyclohexane series, whose detection indicates the presence of SLC oil (Lawler *et al*. 1978b), were found in every tissue treatment group.

An examination of the saturated hydrocarbon plots for the heart (Figure 1), kidney (Figure 2), and liver (Figure 3) tissues reveals a number of similar patterns. For instance, in each of the control tissues the low molecular weight *n*-alkanes, *n*-decane through *n*-nonacosane, were in lower concentration than the higher molecular weight *n*-alkanes, *n*-eicosane through *n*-hentriacontane. The control liver, however, contained higher concentrations of *n*-nonacosane (1.26×10^3 ppb) and *n*-hentriacontane (1.87×10^3 ppb) than the heart and kidney controls. Changes in the concentrations of most of the saturated hydrocarbons from treatment group to treatment group

followed the same pattern in all three tissues. The concentrations of the majority of saturates showed a somewhat steady increase from the control through the 2.5% treatment group, and then either dropped off or leveled off in the 5.0% treatment group.

A comparison of the data from the 2.5% treatment group of each tissue with the SLC oil hydrocarbon concentrations in each saturated hydrocarbon plot indicates that the saturated oil hydrocarbons in the duckling tissues were not present in the same relative concentrations observed in the SLC oil. It was obvious from these comparisons that the concentrations of the n-alkanes were greatly reduced in the tissues. This pattern was observed throughout the entire spectrum of n-alkanes detected in the heart. In the kidney and liver, the concentrations of the n-alkanes were skewed towards the high molecular weight end of the gas chromatogram. In fact, the relative concentrations of some of the higher molecular weight n-alkanes were greater than their relative concentrations in the SLC oil. This was true for n-tricosane through n-hentriacontane in the kidney, and n-eicosane through n-hentriacontane in the liver. The reduction of the n-alkanes detected in duckling tissues is graphically illustrated in Figure 7. In this figure, a gas chromatogram of a saturate hydrocarbon fraction from a heart tissue sample in the 2.5% treatment group is compared to a gas chromatogram of the saturate fraction of SLC oil. As indicated above, the relative concentrations of the n-alkanes in the heart saturate fraction were much reduced. The C_{16}-isoprenoid alkane (peak 4) was the hydrocarbon in highest concentration and the entire isoprenoid alkane series (peaks 6, 8, 11, 14, 20 23) was prominent. The C_{16}-isoprenoid alkane was the compound in highest concentration in the saturate fractions of the 0.25%, 2.5%, and 5.0% heart treatment groups. In the kidney, the C_{16}-isoprenoid alkane was detectable in the 0.25% treatment group, but did not become the compound in highest concentration until the 2.5% treatment group. In the liver, the isoprenoid alkane series was prominent in every treatment group, but the concentrations of the series members were skewed towards the high molecular weight end of the gas chromatogram. Phytane (C_{20}) was the isoprenoid alkane in highest concentration at each treatment group level.

Aromatic Hydrocarbons. Examination of the aromatic hydrocarbon plots for the heart (Figure 4), kidney (Figure 5), and liver (Figure 6) tissues reveals the presence of similar patterns in these data also. For instance, no aromatic hydrocarbons of petroleum origin were detected in any of the control tissues. In the experimental tissues, however, aromatic hydrocarbons derived from SLC oil were detected in every tissue treatment group.

Changes in the concentrations of individual aromatic hydrocarbons in the heart and the kidney followed the same pattern observed for the saturated hydrocarbons. Most of the aromatics increased in concentration from the 0.025% treatment group through the 2.5% treatment group, and then either dropped off or leveled off in the 5.0% treatment group. Although some of the aromatic compounds detected in the liver followed this pattern, most of them increased in concentration

from the 0.025% treatment group through the 5.0% treatment group. A comparison of the data from the 2.5% treatment groups of the heart and kidney with the SLC oil hydrocarbon concentration data in the aromatic hydrocarbon plots indicates that the aromatic oil hydrocarbons in the duckling tissues were not present in the same relative concentrations observed in the SLC oil. This was also true for the aromatic oil hydrocarbons detected in the liver. The most prominent feature of each of these comparisons was the reduced concentrations of the tissue aromatic hydrocarbons eluting after naphthalene. This reduction in the relative concentrations of the aromatic oil hydrocarbons detected in the duckling tissues is graphically illustrated in Figure 8. In this figure, gas chromatograms of an aromatic hydrocarbon fraction from a heart tissue sample in the 2.5% treatment group and a SLC oil aromatic hydrocarbon fraction are compared. It is evident that the concentrations of the aromatic oil hydrocarbons eluting after naphthalene were much reduced in the heart aromatic fraction. This same general pattern was observed in the aromatic fraction gas chromatograms from every tissue treatment group.

Total Petroleum Hydrocarbons

<u>Total Resolved Saturated and Total Resolved Aromatic Oil Hydrocarbons</u>. A comparison of the total resolved saturated and the total resolved aromatic oil hydrocarbons detected in the three experimental tissues is presented in Table 2. Changes in the concentrations of the total resolved oil saturates and the total resolved oil aromatics followed the patterns observed for most of the saturated and aromatic hydrocarbons listed in Figures 1-6. The liver total resolved oil aromatics was the only set of measurements that did not show a steady increase from the 0.025% treatment group through the 2.5% treatment group followed by a slight decline in the 5.0% treatment group. This set of data exhibited a steady increase from the 0.025% treatment group through the 5.0% treatment group. The heart contained the highest concentration of total resolved aromatic oil hydrocarbons in every treatment group but the lowest one. The kidney had the second highest concentration of total resolved aromatic oil hydrocarbons in every treatment group but the highest one.

The heart contained the highest concentration of total resolved saturated oil hydrocarbons in treatment groups 2.5% and 5.0%. The liver and kidney total resolved oil saturate concentrations were almost equal in the 0.025%, 0.25%, and 5.0% treatment groups. In the 2.5% treatment group, however, the liver contained considerably more total resolved oil saturates.

<u>Total Saturated and Total Aromatic Oil Hydrocarbons</u>. A comparison of the treatment group to treatment group changes in the concentrations of total saturated and total aromatic oil hydrocarbons is also presented in Table 2. Changes in these parameters followed the same pattern in all three experimental tissues. In each case, there was a steady increase in concentration from the 0.025% treatment group through the 2.5% treatment group followed by a slight decline in the 5.0% treatment group. The liver had the highest

concentration of total oil saturates in each treatment group. The heart contained higher concentrations of total oil saturates than the kidney in treatment groups 2.5% and 5.0%, but the kidney had the higher concentrations in treatment groups 0.025% and 0.25%. The heart total saturated and total aromatic oil hydrocarbon concentrations were not detected by our methods in the lowest treatment group. Heart total resolved saturated and total resolved aromatic oil hydrocarbon concentration values were, therefore, substutited for the zero readings obtained at the 0.025% treatment group level. These values were the best estimates of the total saturated and total aromatic oil hydrocarbon concentrations available for this tissue treatment group.

The liver had higher concentrations of total aromatic oil hydrocarbons than the heart in every treatment group but the 2.5% treatment group. The kidney contained the lowest concentration of total oil aromatics in every treatment group but the 0.025% treatment group.

Total Oil Hydrocarbons. Changes in the concentrations of total oil hydrocarbons detected in the three experimental tissues are represented in Figure 9, which is a log-log plot of tissue total oil hydrocarbon concentration (ppb) vs. feed oil concentration (ppb). As expected, the changes in total oil hydrocarbon concentrations from treatment group to treatment group followed the same pattern observed for changes in the concentrations of total oil saturates and total oil aromatics detected in these same tissues. The changes in the total oil hydrocarbon concentrations in the liver and kidney were almost parallel. The liver contained the highest concentration of total oil hydrocarbons in each treatment group. The heart had higher concentrations of total oil hydrocarbons than the kidney in treatment groups 2.5% and 5.0%, but the kidney had the higher concentrations in treatment groups 0.025% and 0.25%. The total oil hydrocarbon concentration in the heart 0.025% treatment group tissue was obtained by adding the concentrations of the total resolved oil saturates and total resolved oil aromatics detected at that treatment group level, and is probably a low estimate of the total petroleum hydrocarbons actually present.

Gas Chromatogram Patterns. Although qualitatively very similar, the gas chromatograms of the saturate and aromatic hydrocarbon fractions of the experimental tissues were still distinctly different. The series of gas chromatograms in Figure 10 illustrates that the analyses of the liver saturate fractions were dominated by a high molecular weight UCHM (mean elution temperature 205°C). It is also evident that changes in the concentration of this saturate UCHM from treatment group to treatment group accounted for the pattern of changes in total oil saturated hydrocarbon concentrations described above. A high molecular weight aromatic UCHM (mean elution temperature 245°C) dominated the analyses of the liver aromatic hydrocarbon fractions in the same manner. There was little, if any, of either of these two high molecular weight UCHM's detectable in the heart of any treatment group level. Lower molecular weight UCHM's were, however, observed in heart saturated (mean elution temperature 125°C) and aromatic (mean elution temperature 180°C) hydrocarbon fractions. In the kidney, there were distinct indications of the presence of both the high molecular weight saturate and the high molecular weight aromatic

UCHM's in each treatment group. The kidney aromatic fractions were dominated by the high molecular weight aromatic UCHM in the manner described above for the liver.

Graphic illustrations of the relative concentrations of the saturate and aromatic UCHM's detected in the experimental tissues are presented in Figures 11 and 12. A comparison of gas chromatograms of the saturate fractions from the liver and kidney 2.5% treatment groups, and the heart 5.0% treatment group is presented in Figure 11. A heart 5.0% treatment group gas chromatogram was used in this comparison because high concentrations of oil-derived saturated hydrocarbons coul' have obscured low levels of the high molecular weight saturate UCHM in the heart 2.5% treatment group (see Figure 7). These gas chromatograms indicate that the liver had the highest concentration of the high molecular weight saturate UCHM and that the kidney had the second highest concentration. The heart contained little, if any, of the high molecular weight saturate UCHM, although some of the lower molecular weight saturate UCHM was evident. A comparison of gas chromatograms of the aromatic fractions from the liver, kidney, and heart 2.5% treatment groups, illustrated in Figure 12, indicates that a similar situation existed for the aromatic UCHM's. The liver contained the greatest concentration of the high molecular weight aromatic UCHM and the kidney contained the second highest concentration. Although some of the lower molecular weight aromatic UCHM was present in the heart, the high molecular weight aromatic UCHM was not detectable.

DISCUSSION

The total petroleum hydrocarbon data obtained in this study was in agreement with similar data from other petroleum-type hydrocarbon uptake and distribution studies, in that, of the three tissues examined, the liver accumulated the highest concentration of oil hydrocarbons in each treatment group (Lee et al. 1972; Boitnott and Margolis, 1970; Kolattukudy and Hankin, 1966). The almost parallel relationship between the treatment group to treatment group changes in the concentrations of total oil hydrocarbons detected in the liver and kidney suggests that the concentrations of petroleum hydrocarbons in these two tissues may be linked.

Most of the petroleum hydrocarbons detected in the experimental tissues were present as members of UCHM's. The significance of the contribution of the UCHM's to the total oil hydrocarbon measurements is indicated by the observation that the total saturated and total aromatic oil hydrocarbon concentrations were substantially higher than the total resolved saturated and total resolved aromatic oil hydrocarbon concentrations in almost every tissue treatment group. The total resolved saturate and total resolved aromatic oil hydrocarbon concentrations were obtained with the saturate and aromatic UCHM's excluded from the measurements. The heart contained higher concentrations of total resolved saturated oil hydrocarbons than the liver in the two highest treatment groups. This is similar to the distribution of SLC oil saturates previously reported by us (Lawler et al. 1978b) in acutely SLC oil-dosed adult mallard drakes whose

heart and liver saturate fractions did not contain UCHM's.

The observation that saturated oil hydrocarbons accumulated in higher concentrations than aromatic oil hydrocarbons in every tissue treatment group was not unexpected. Type analyses, done in this laboratory, of the SLC oil used in this experiment indicated that the experimental oil contained an estimated 24.5 percent by weight of aromatic hydrocarbons. Because the oil hydrocarbons in the duckling tissues had been extensively metabolized (see below), no attempt was made to directly relate the saturated and aromatic hydrocarbon contents of the oil detected in the experimental tissues to the original saturated and aromatic hydrocarbon contents of SLC oil.

Certain inferences about the metabolism of oil hydrocarbons by mallard ducklings can be drawn from the quantitative data gathered in this study. The most striking feature of the saturated petroleum hydrocarbon data from each of the experimental tissues was the pronounced reduction in the concentration of SLC oil-derived n-alkanes. This suggests that the ducklings preferentially metabolized the n-alkanes present in the ingested oil.

In the liver, which has been shown to be the major site of hydrocarbon metabolism in other organisms (Kolattukudy and Hankin, 1966; Lee et al. 1972), not only were the n-alkanes reduced, but the concentrations of those remaining were skewed towards the high molecular weight end of the gas chromatogram. A similar distribution was also noted for members of the isoprenoid alkane series. This suggests that the ducklings metabolized the low molecular weight saturated hydrocarbons at a faster rate than the high molecular weight saturates. Mechalas (1973) reported that biodegradation of Santa Barbara crude oil by a mixed microbial population was characterized by rapid reduction of the n-alkanes, starting with the lower molecular weight compounds. At the same time, the microbes also progressively degraded the isoprenoid alkanes and the UCHM. The higher rate of microbial degradation of the low molecular weight components of the UCHM caused it to become skewed towards the high molecular weight end of the gas chromatogram. The saturated and aromatic UCHM's detected in the duckling liver and kidney tissues showed a similar distribution, in that, they also were skewed towards the high molecular weight ends of their respective gas chromatograms. These observations suggest that the high molecular weight UCHM's detected in the liver and kidney were made up of high molecular weight SLC oil-derived hydrcarbons that accumulated in the duckling tissues due to differential hydrocarbon degradation. That these high molecular weight hydrocarbons accumulated in direct response to chronic oil ingestion is indicated by the fact that high molecular weight saturate and aromatic UCHM's were not detected in hydrocarbon fractions from the liver and other tissues of adult mallard drakes acutely dosed with SLC oil (Lawler et al. 1978b; Lawler et al. 1978c).

The quantitative data gathered on the individual aromatic hydrocarbons did not indicate that their concentrations increased towards

the high molecular weight end of the gas chromatogram. The highest molecular weight aromatic hydrocarbon quantitated, however, was trimethylnaphthalene, MW 170. Naphthalene was the aromatic hydrocarbon in either the highest or close to the highest concentration in each tissue treatment group. This is consistent with the aromatic hydrocarbon patterns observed in the tissues of acutely SLC oil-dosed adult mallard drakes (Lawler et al. 1978c), and indicates a reduction in the relative concentrations of the aromatic oil hydrocarbons eluting after naphthalene. The reason for the reduction in the concentrations of these compounds, relative to their concentrations in SLC oil, is obscure, but could involve differential uptake and/or metabolism of the SLC oil aromatic hydrocarbons by the ducklings.

As indicated above, the metabolism of petroleum hydrocarbons by mallard ducklings can only be inferred by the data gathered in this study. Other birds, however, have been shown to have the ability to metabolize foreign hydrocarbons (Conney and Burns, 1972), and Miller et al. (1978) recently induced an hepatic microsomal, cytochrome P-450 mixed-function oxidase system in herring gull chicks with a single dose of crude oil.

Changes in the concentrations of most of the individually measured saturated and aromatic oil hydrocarbons detected in the three experimental tissues appeared to follow the same pattern. That is, their concentrations increased steadily from the 0.025% treatment group through the 2.5% treatment group and then declined slightly in the 5.0% treatment group. This pattern did not, however, hold for the aromatic oil hydrocarbons detected in the liver. Most of these aromatics increased steadily from the 0.025% treatment group through the 5.0% treatment group. These apparent trends in the measurements of individual oil hydrocarbons were confirmed by similar patterns observed for the total resolved saturated and the total resolved aromatic oil hydrocarbon concentrations. The liver total resolved oil aromatics was the only set of data that showed a steady increase from the lowest to the highest treatment group level.

Resolved oil hydrocarbons, however, did not account for the bulk of the oil hydrocarbons in most of the tissue hydrocarbon fractions. It was possible, then, that if the UCHM's were included in the petroleum hydrocarbon measurements, the patterns observed for the total resolved oil hydrocarbons would be changed. This turned out to be true in only one case, the liver aromatics. The liver total aromatic oil hydrocarbon concentrations increased through the 2.5% treatment group and then leveled off in the 5.0% treatment group. All of the other total saturated and total aromatic oil hydrocarbon measurements increased from the 0.025% treatment group through the 2.5% treatment group and then declined slightly in the 5.0% treatment group. Total oil hydrocarbon concentrations, which were calculated from the total saturated and total aromatic oil hydrocarbon data, also followed this pattern. It is evident, then, that the concentrations of petroleum hydrocarbons in the duckling tissues decreased when going from the second highest treatment group (2.5%) to the highest treatment group (5.0%).

This suggests that a maximum effective SLC oil-dosage level, using commercial duck starter as the vehicle, lies somewhere between 2.5% and 5.0% w/w. Increasing the oil dosage above the 2.5% level did not result in increased accumulation of oil hydrocarbons in the duckling tissues. The well-known laxative effects of oils and the demonstrated diarrheal effects of various oils on ducks (Hartung and Hunt, 1966) suggest that reduced oil uptake may be responsible for the relatively low petroleum hydrocarbon concentrations detected in the tissues of the 5.0% treatment group ducklings. Factors other than reduced oil uptake, such as adaptive hypertrophy of specific lipid metabolizing organs, could also be involved in establishing the final oil hydrocarbon concentrations detected in the 5.0% treatment group duckling tissues. Szaro et al. (1978) observed liver hypertrophy in the ducklings that had been fed 2.5% and 5.0% oil diets.

The detection of lower concentrations of petroleum hydrocarbons in the 5.0% treatment group ducklings than in the 2.5% treatment group ducklings was unexpected because several of the most severe toxic responses, such as reduced growth, liver hypertrophy, and splenic atrophy, occurred in ducklings from the 5.0% treatment group (Szaro et al. 1978). The fact that prestressed adult mallard ducks subjected to oil stress exhibited toxic responses in excess of those elicited in unstressed ducks receiving the same dose of oil (Hartung and Hunt, 1966) suggests that the ducklings in the 5.0% treatment group may have been stressed by some factor in addition to oil ingestion. Even though the 5.0% treatment group ducklings consumed essentially the same amount of feed as the control ducks (Szaro et al. 1978), the unknown stress factor could have been malnutrition. If oil was indeed acting as a laxative or diarrheal agent at the 5.0% dosage level, then not only oil uptake but also nutrient uptake would have been reduced in the highest treatment group ducklings. The severe pathological responses of ducklings in the 5.0% treatment group, therefore, may have been the result of two stress factors, malnutrition and oil ingestion, operating simultaneously during their critical early stages of development.

Other than the observation that oil hydrocarbons were present in the experimental tissues that exhibited pathological changes in response to oil ingestion, there were no obvious relationships between tissue oil hydrocarbon content and pathological response. Two of the experimental tissues, the liver and the kidney, exhibited biochemical lesions and one, the heart, did not (Szaro et al. 1978). Oil hydrocarbons, however, were detected in all three experimental tissues. A search was made, therefore, to determine if any specific oil hydrocarbons or groups of oil hydrocarbons were present or in high concentration in the liver and kidney, but not in the heart. There were only two groups of compounds that met this criterion, the high molecular weight saturate UCHM and the high molecular weight aromatic UCHM. Although exact quantitative data was not obtained for the high molecular weight UCHM's in this study, a comparison of the gas chromatograms from each tissue treatment group clearly indicated the

relative concentrations of these UCHM's in the experimental tissues. The liver contained the highest concentrations of both the high molecular weight saturate UCHM and the high molecular weight aromatic UCHM at each treatment group level. The kidney contained detectable concentrations of both high molecular weight UCHM's at each treatment group level, and the heart contained little, if any, of either of the high molecular weight UCHM's at any treatment group level. Of course, these observations do not indicate that the high molecular weight saturated UCHM and/or the high molecular weight aromatic UCHM were actually the compounds that elicited the pathological responses in the duckling liver and kidney tissues. They do, however, suggest this as a possibility.

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Table 1. A List of the Saturated and the Aromatic Hydrocarbons in the Recovery Standard Indicating Their Percent Recoveries

SATURATE HYDROCARBONS	PERCENT RECOVERY* C.V.[†]
Decane	38.7 ± 2.5%
Butylcyclohexane	41.6 ± 2.5%
Undecane	45.5 ± 4.1%
Dodecane	53.5 ± 8.6%
Heptylcyclohexane	56.6 ± 2.6%
Octylcyclohexane	60.0 ± 4.1%
Nonylcyclohexane	63.5 ± 4.8%
Pristane	67.0 ± 4.0%
Octadecane	62.7 ± 4.8%
Nonadecane	65.0 ± 3.0%
Eicosane	66.6 ± 5.3%
AROMATIC HYDROCARBONS	
Butylbenzene	54.6 ± 19.4%
Naphthalene	68.2 ± 19.0%
2-Methylnaphthalene	63.2 ± 19.0%
Biphenyl	71.3 ± 7.8%
2,3-Dimethylnaphthalene	64.1 ± 17.6%
3-Methylbiphenyl	64.2 ± 17.3%
2,3,6-Trimethylnaphthalene	62.7 ± 20.4%

*Calculations based on 4 replicate analyses of 30 g wet weight of duck breast muscle spiked with the equivalent of 50 ppb of each of the hydrocarbons in the recovery standard.

†Coefficient of variation.

Table 2. A Comparison of Total Resolved Oil Saturates, Total Resolved Oil Aromatics, Total Oil Saturates, and Total Oil Aromatics in Duckling Heart, Kidney, and Liver Tissues.

		0.025%	0.25%	2.5%	5.0%
Heart	Total Resolved Oil Saturates	4.3×10^{-2}*	8.8×10^{-1}*	16*	4.0*
	Total Resolved Oil Aromatics	2.8×10^{-3}	2.0×10^{-2}	2.6×10^{-1}	1.3×10^{-1}
	Total Oil Saturates	(4.3×10^{-2})†	5.94	41.6	23.3
	Total Oil Aromatics	(2.8×10^{-3})††	1.47	16.8	10.8
Kidney	Total Resolved Oil Saturates	3.3×10^{-1}	1.0	3.6	3.1
	Total Resolved Oil Aromatics	8.2×10^{-3}	1.6×10^{-2}	1.1×10^{-1}	9.2×10^{-2}
	Total Oil Saturates	2.65	11.8	22.3	19.2
	Total Oil Aromatics	8.2×10^{-3}	2.1×10^{-2}	6.2	2.3
Liver	Total Resolved Oil Saturates	3.0×10^{-1}	1.6	5.9	2.9
	Total Resolved Oil Aromatics	2.9×10^{-3}	1.1×10^{-2}	6.7×10^{-2}	1.2×10^{-1}
	Total Oil Saturates	16.2	51.7	130	75.0
	Total Oil Aromatics	3.0×10^{-3}	8.2	16.2	16.0

*Parts per million wet weight.

†Total resolved oil saturates value substituted for zero reading of total oil saturates.

††Total resolved oil aromatics value substituted for zero reading of total oil aromatics.

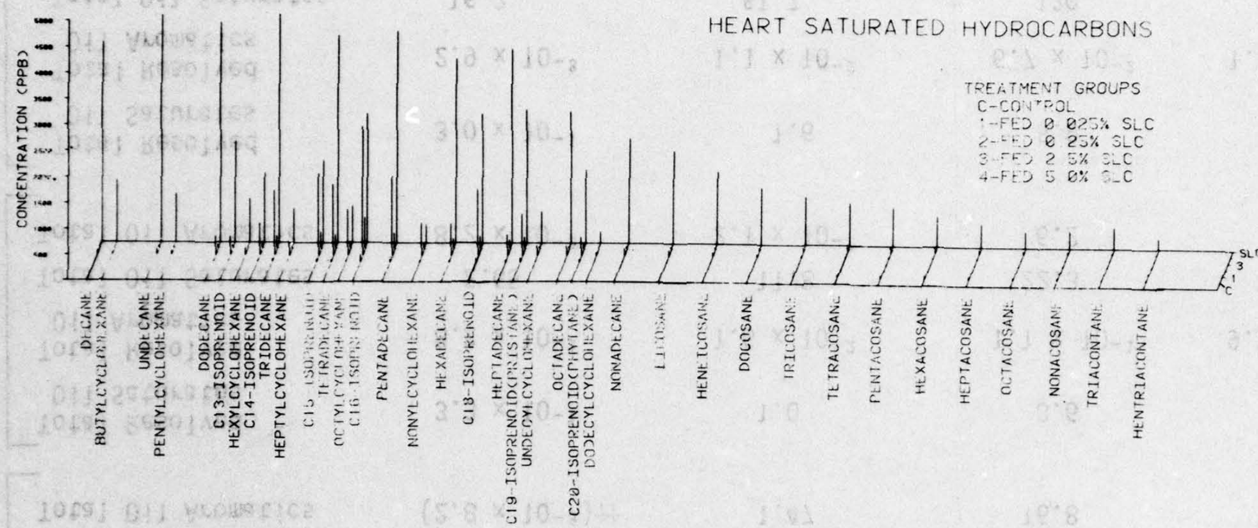

Figure 1. A comparison of the concentrations of thirty-seven saturated hydrocarbons in the heart control and each treatment group with their concentrations in SLC oil. To obtain the SLC oil hydrocarbon values, the C_{16}-isoprenoid alkane concentration in SLC oil was made equal to the highest concentration of C_{16}-isoprenoid alkane in the tissue. The concentrations of the other SLC oil saturated hydrocarbons were then normalized to that of the C_{16}-isoprenoid alkane. Each reading is the mean of four replicate analyses.

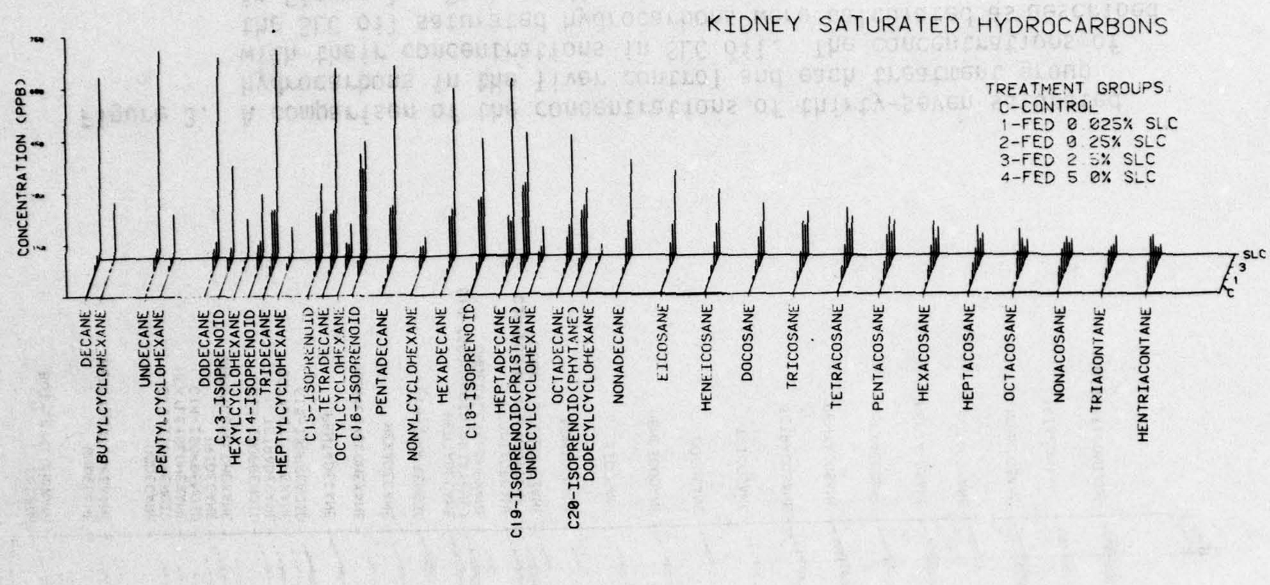

Figure 2. A comparison of the concentrations of thirty-seven saturated hydrocarbons in the kidney control and each treatment group with their concentrations in *SLC oil*. The concentrations of the SLC oil saturated hydrocarbons were calculated as described in Figure 1. Each reading is the mean of two replicate analyses.

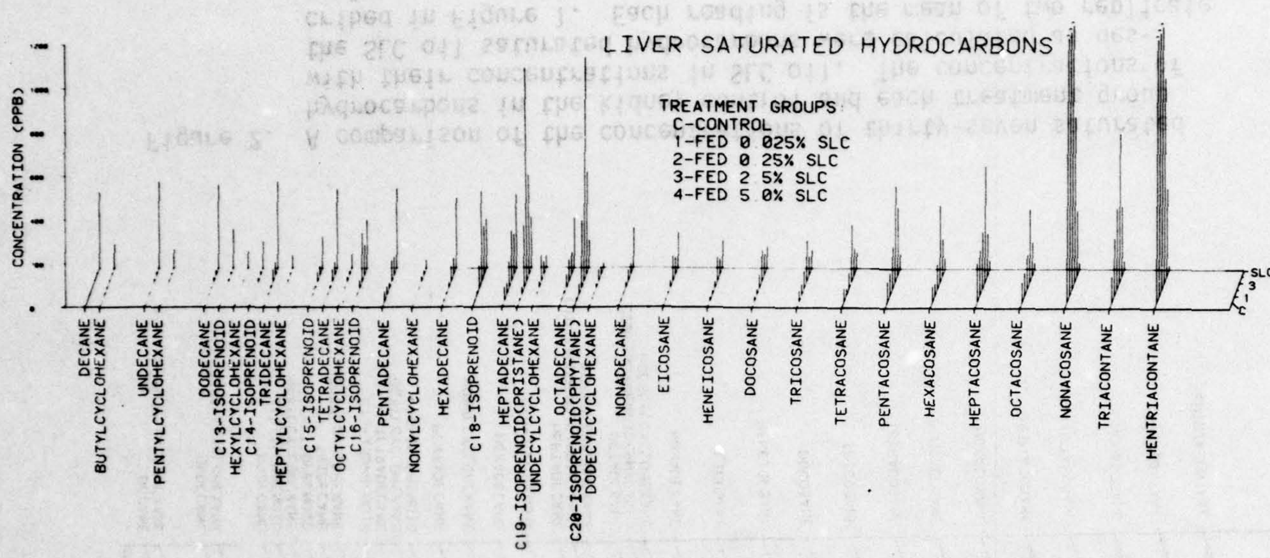

Figure 3. A comparison of the concentrations of thirty-seven saturated hydrocarbons in the liver control and each treatment group with their concentrations in SLC oil. The concentrations of the SLC oil saturated hydrocarbons were calculated as described in Figure 1. Each reading is the mean of four replicate analyses.

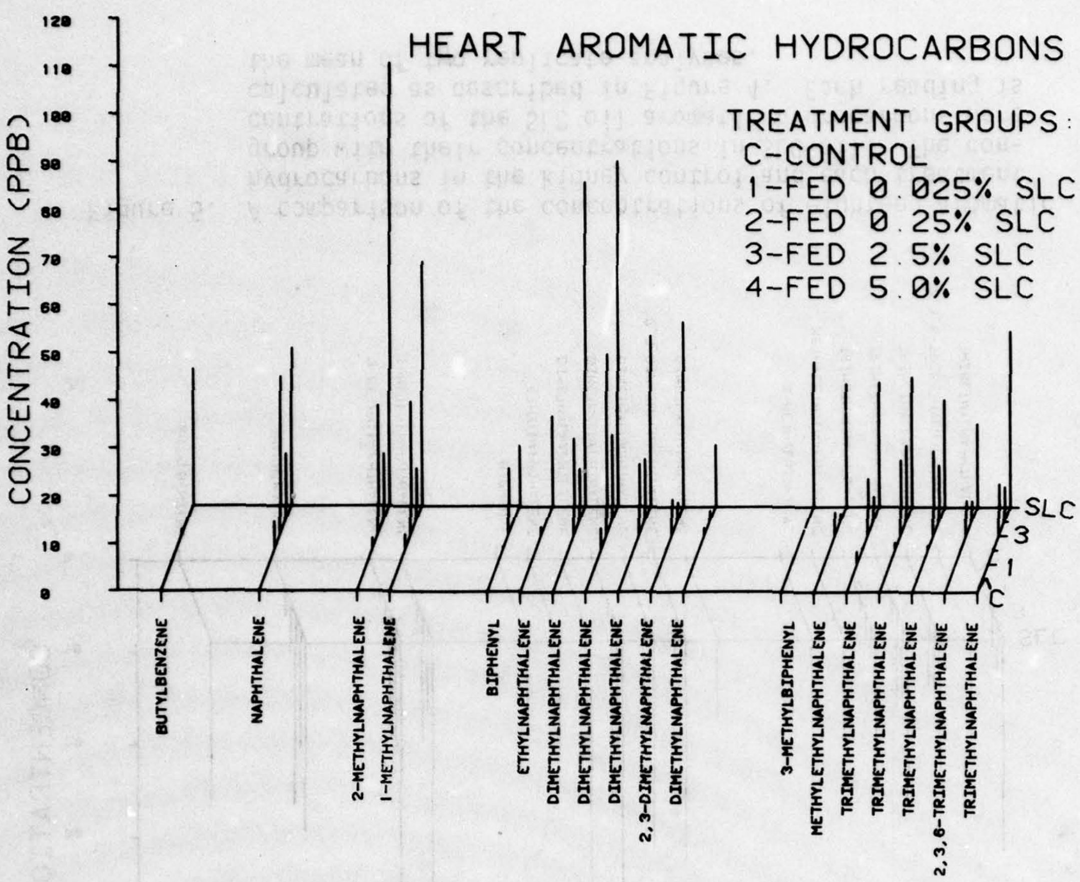

Figure 4. A comparison of the concentrations of eighteen aromatic hydrocarbons in the heart control and each treatment group with their concentrations in SLC oil. To obtain the SLC oil hydrocarbon values, the naphthalene concentration in the SLC oil was made equal to the highest concentration of naphthalene in the tissue. The concentrations of the other SLC oil aromatic hydrocarbons were then normalized to that of naphthalene. Each reading is the mean of four replicate analyses.

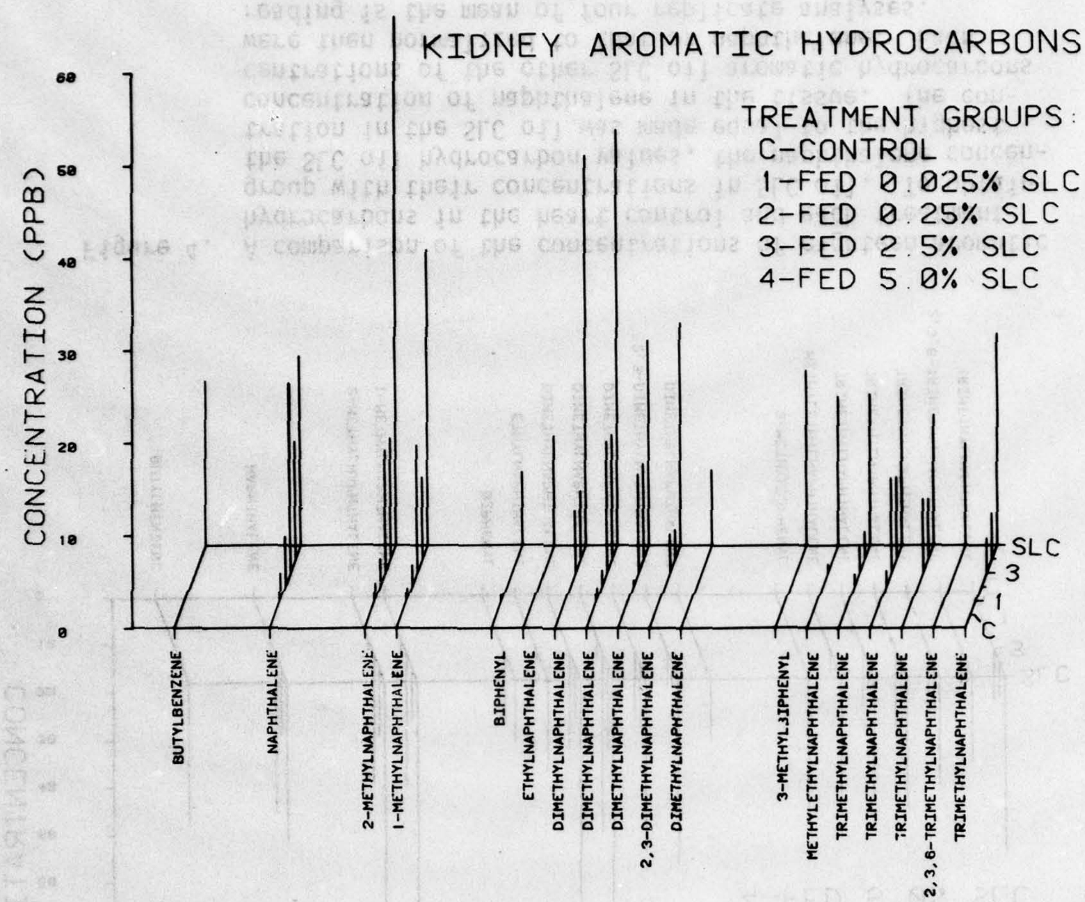

Figure 5. A comparison of the concentrations of eighteen aromatic hydrocarbons in the kidney control and each treatment group with their concentrations in SLC oil. The concentrations of the SLC oil aromatic hydrocarbons were calculated as described in Figure 4. Each reading is the mean of two replicate analyses.

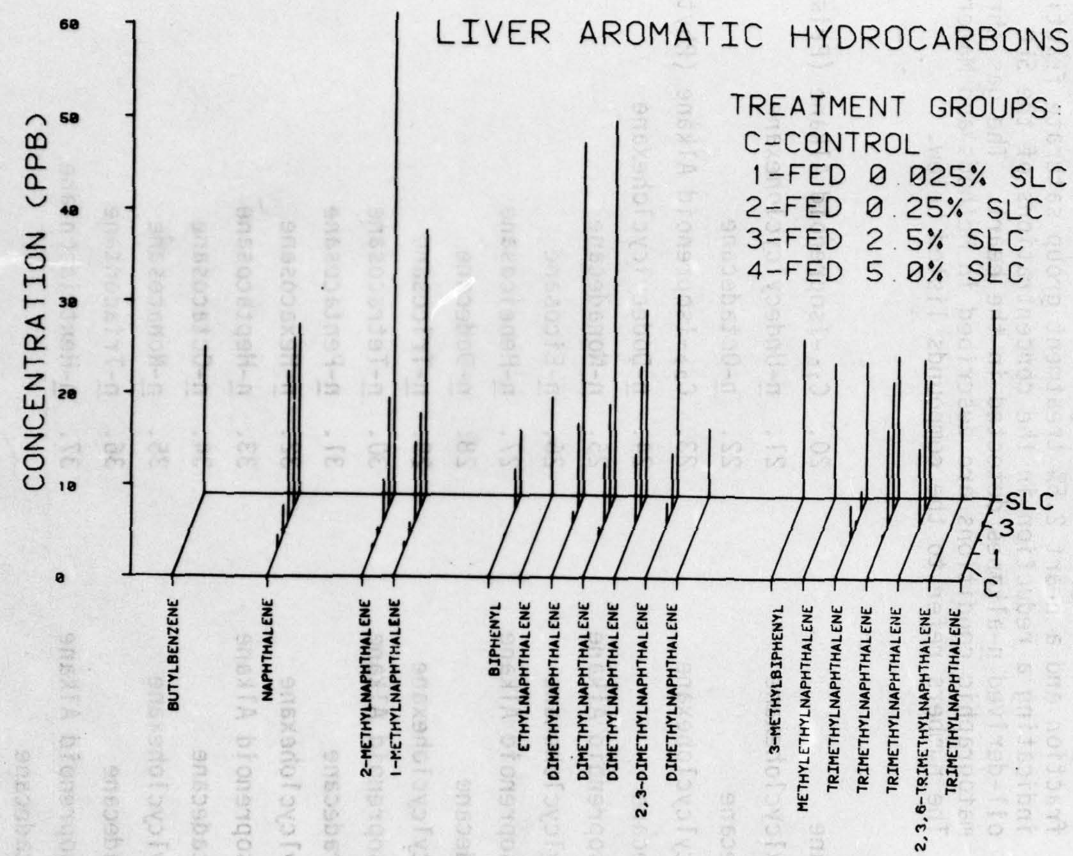

Figure 6. A comparison of the concentrations of eighteen aromatic hydrocarbons in the liver control and each treatment group with their concentrations in SLC oil. The concentrations of the SLC oil aromatic hydrocarbons were calculated as described in Figure 4. Each reading is the mean of four replicate analyses.

Figure 7. A comparison of gas chromatograms of the SLC oil saturate fraction and a heart 2.5% treatment group saturate fraction indicating a reduction in the concentrations of the SLC oil-derived _n_-alkanes detected in the heart. The gas chromatographic conditions are described in Methods and Materials. The numbers refer to the compounds listed below.

1. _n_-Decane
2. _n_-Butylcyclohexane
3. _n_-Undecane
4. _n_-Pentylcyclohexane
5. _n_-Dodecane
6. C_{11}-Isoprenoid Alkane
7. _n_-Hexylcyclohexane
8. C_{14}-Isoprenoid Alkane
9. _n_-Tridecane
10. _n_-Heptylcyclohexane
11. C_{15}-Isoprenoid Alkane
12. _n_-Tetradecane
13. _n_-Octylcyclohexane
14. C_{16}-Isoprenoid Alkane
15. _n_-Pentadecane
16. _n_-Nonylcyclohexane
17. _n_-Hexadecane
18. C_{18}-Isoprenoid Alkane
19. _n_-Heptadecane
20. C_{19}-Isoprenoid Alkane (Pristane)
21. _n_-Undecylcyclohexane
22. _n_-Octadecane
23. C_{20}-Isoprenoid Alkane (Phytane)
24. _n_-Dodecylcyclohexane
25. _n_-Nonadecane
26. _n_-Eicosane
27. _n_-Heneicosane
28. _n_-Dodecane
29. _n_-Tricosane
30. _n_-Tetracosane
31. _n_-Pentacosane
32. _n_-Hexacosane
33. _n_-Heptacosane
34. _n_-Octacosane
35. _n_-Nonacosane
36. _n_-Triacontane
37. _n_-Hentriacontane

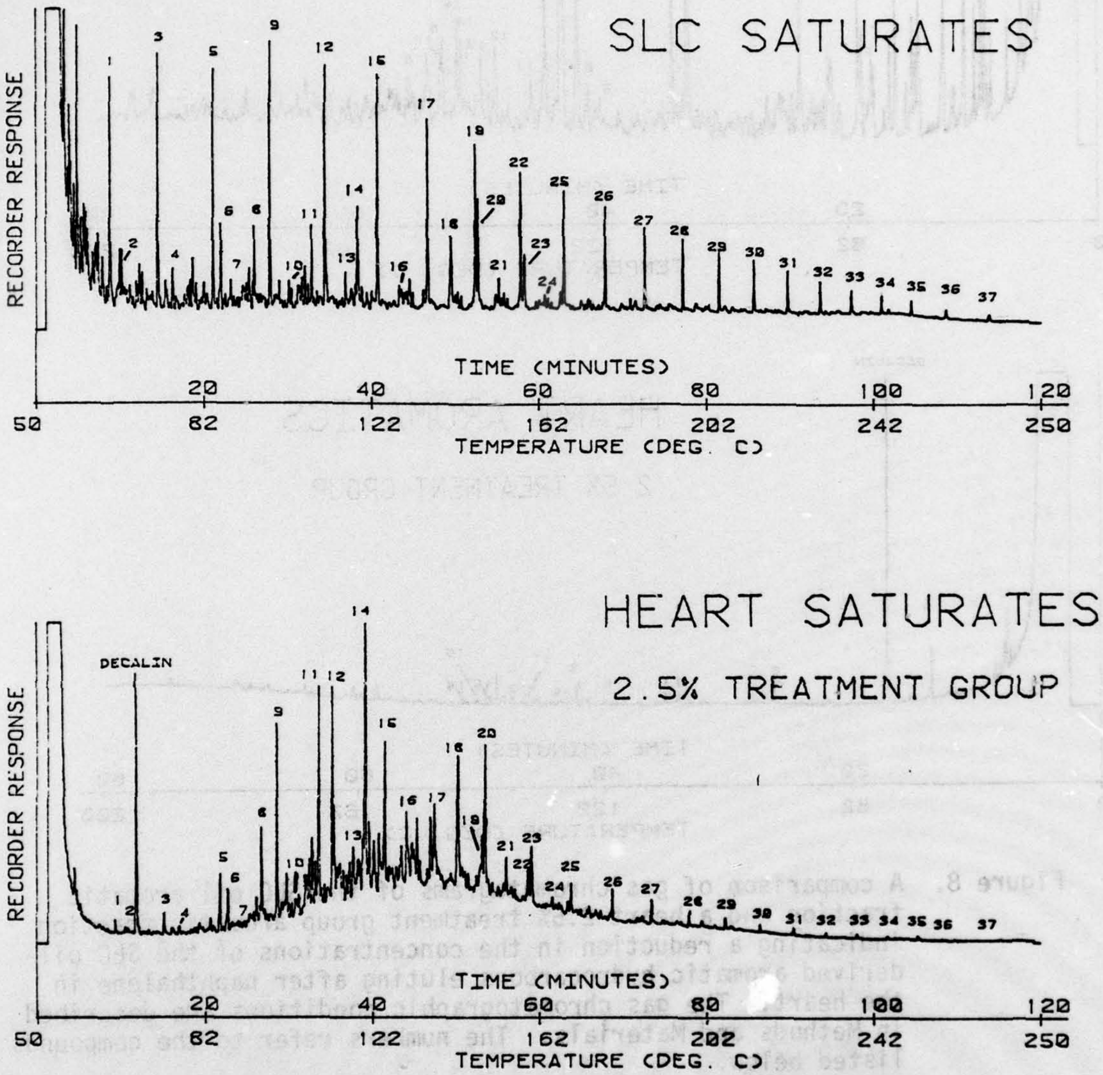
SLC SATURATES
RECORDER RESPONSE
TIME (MINUTES)
20 40 60 80 100 120
50 82 122 162 202 242 250
TEMPERATURE (DEG. C)
HEART SATURATES
2.5% TREATMENT GROUP
DECALIN
RECORDER RESPONSE
TIME (MINUTES)
20 40 60 80 100 120
50 82 122 162 202 242 250
TEMPERATURE (DEG. C)

Figure 7.

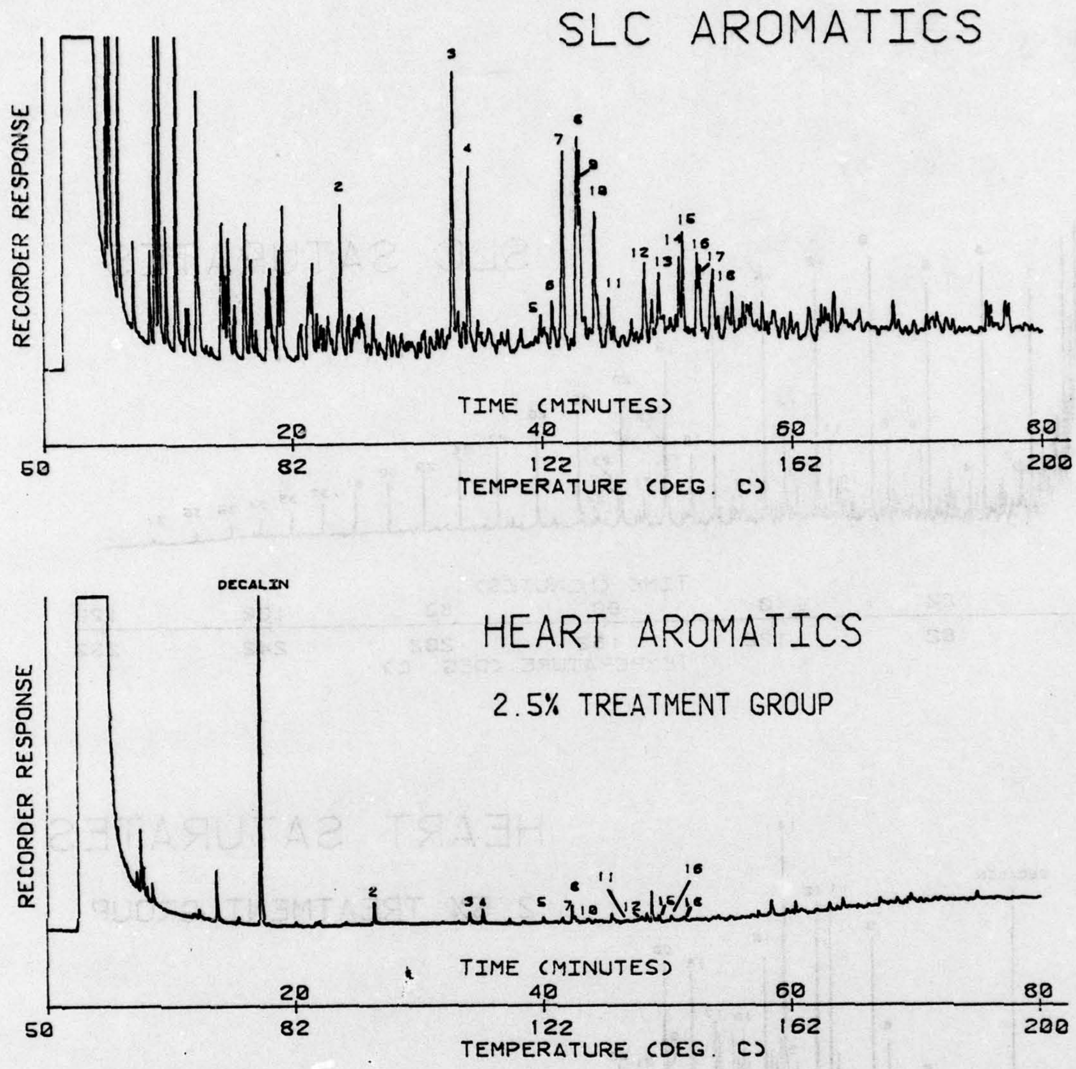

Figure 8. A comparison of gas chromatograms of the SLC oil aromatic fraction and a heart 2.5% treatment group aromatic fraction indicating a reduction in the concentrations of the SLC oil-derived aromatic hydrocarbons eluting after naphthalene in the heart. The gas chromatographic conditions are described in Methods and Materials. The numbers refer to the compounds listed below.

1. Butylbenzene
2. Naphthalene
3. 2-Methylnaphthalene
4. 1-Methylnaphthalene
5. Biphenyl
6. Ethylnaphthalene
7. Dimethylnaphthalene
8. Dimethylnaphthalene
9. Dimethylnaphthalene
10. 2,3-Dimethylnaphthalene
11. Dimethylnaphthalene
12. 3-Methylbiphenyl
13. Methylethylnaphthalene
14. Trimethylnaphthalene
15. Trimethylnaphthalene
16. Trimethylnaphthalene
17. 2,3,6-Trimethylnaphthalene
18. Trimethylnaphthalene

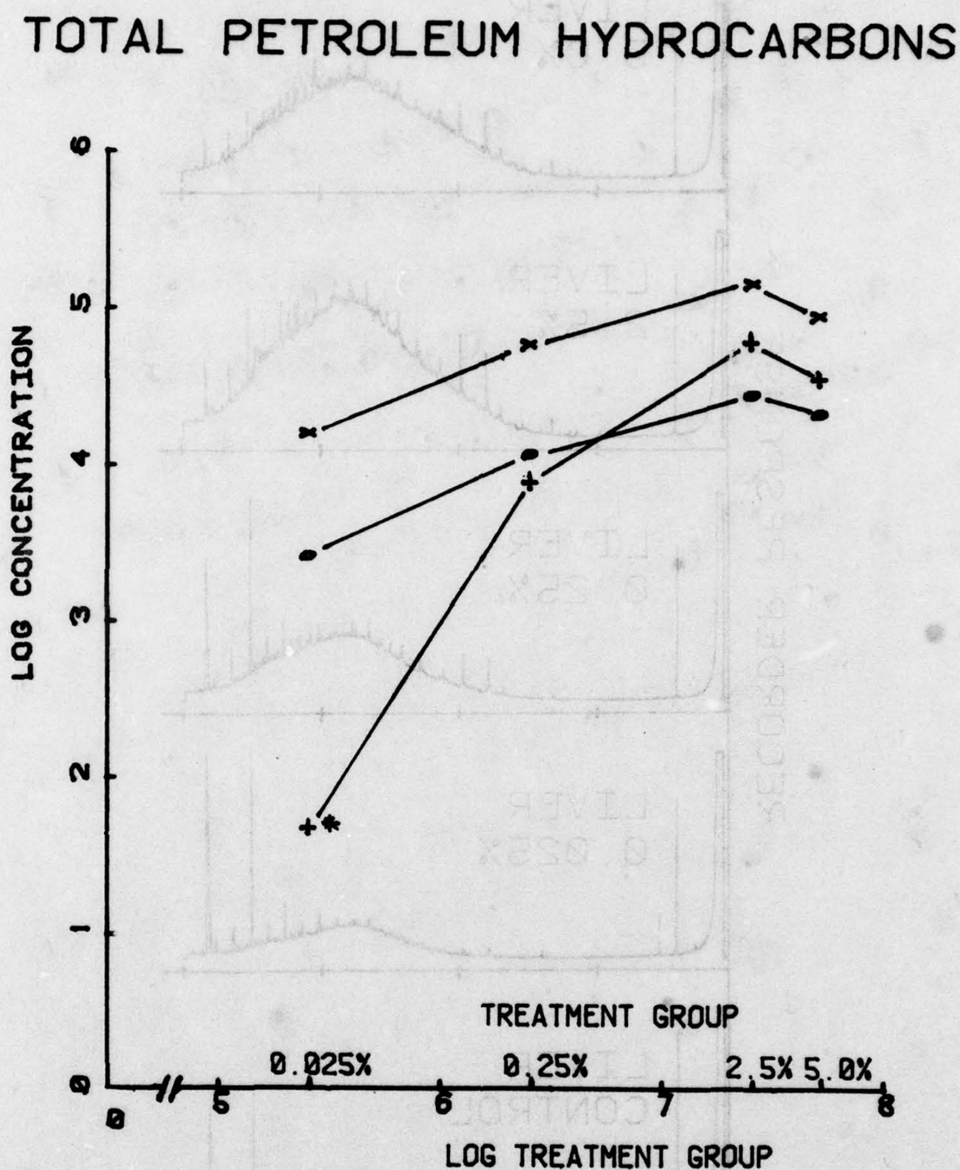

Figure 9. A log-log plot of tissue total petroleum hydrocarbon concentration (ppb) vs. feed oil concentration (ppb), indicating that the total petroleum hydrocarbon concentrations in each tissue increased from the 0.025% treatment group through the 2.5% treatment group and then declined slightly in the 5.0% treatment group. Heart (+ - +), Kidney (O - O), and Liver (X - X). *The total petroleum hydrocarbon concentration in the heart 0.025% treatment group was obtained by adding the total resolved oil saturates and total resolved oil aromatics detected at that treatment group level, and is probably a low estimate of the total petroleum hydrocarbons actually present.

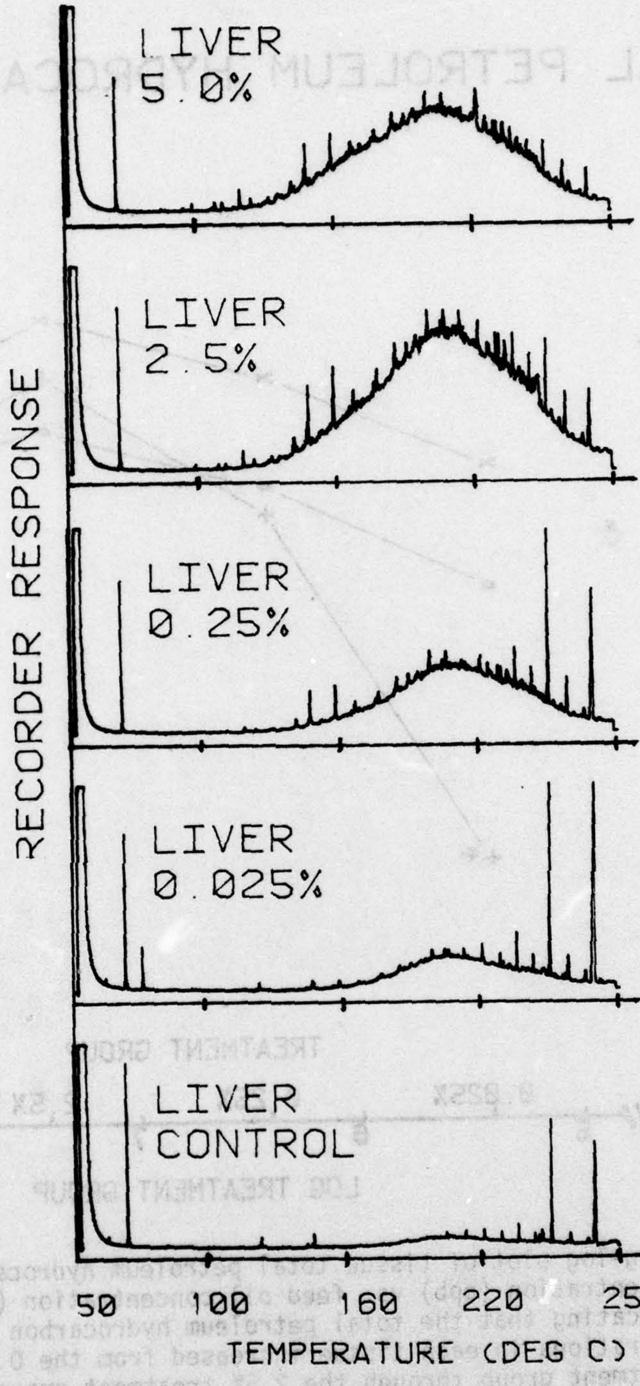

Figure 10. Gas chromatograms of liver saturate hydrocarbon fractions illustrating that the concentration of the liver high molecular weight saturate UCHM increased steadily from the 0.025% treatment group through the 2.5% treatment group and then declined slightly in the 5.0% treatment group. The gas chromatographic conditions are described in Methods and Materials.

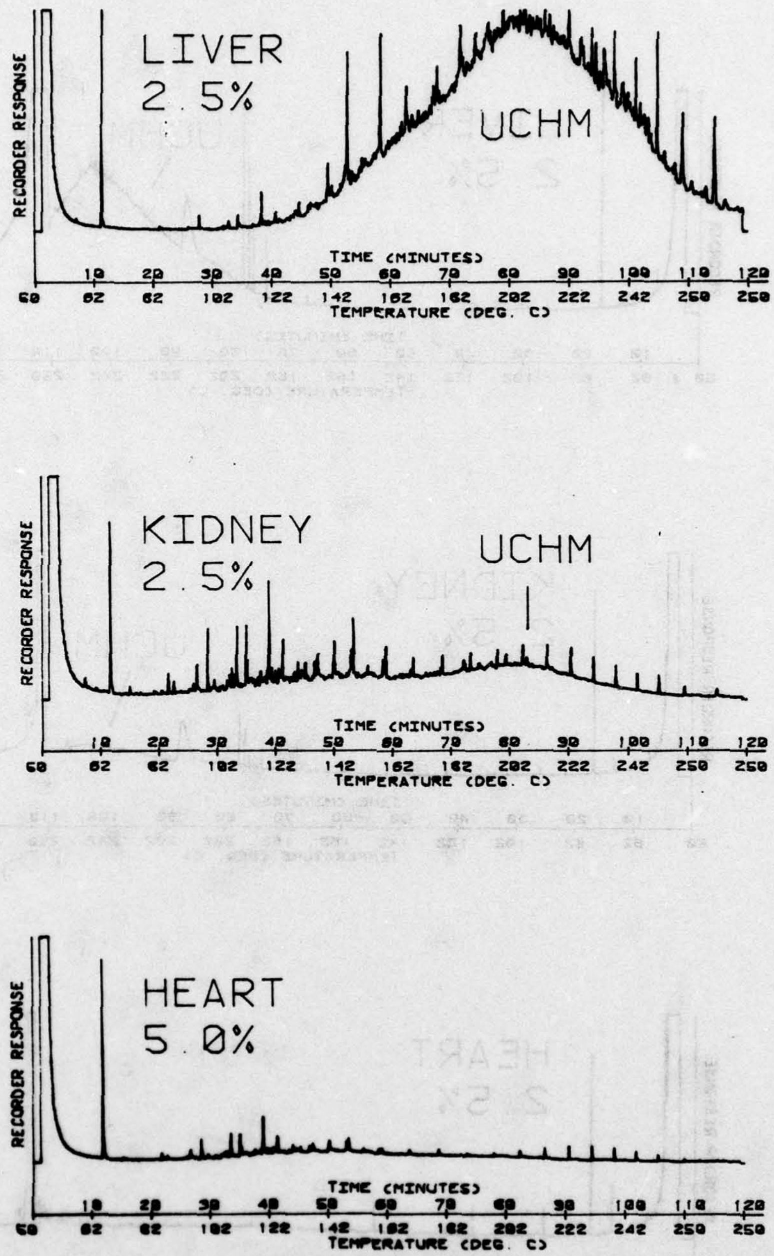

Figure 11. A comparison of gas chromatograms of liver 2.5% treatment group, kidney 2.5% treatment group, and heart 5.0% treatment group saturate hydrocarbon fractions illustrating the presence of a high molecular weight saturate UCHM in the liver and kidney, but not in the heart. A heart 5.0% treatment group gas chromatogram was used in this comparison because high concentrations of oil-derived hydrocarbons in the 2.5% treatment group could have obscured low levels of the high molecular weight saturate UCHM. The gas chromatographic conditions are described in Methods and Materials.

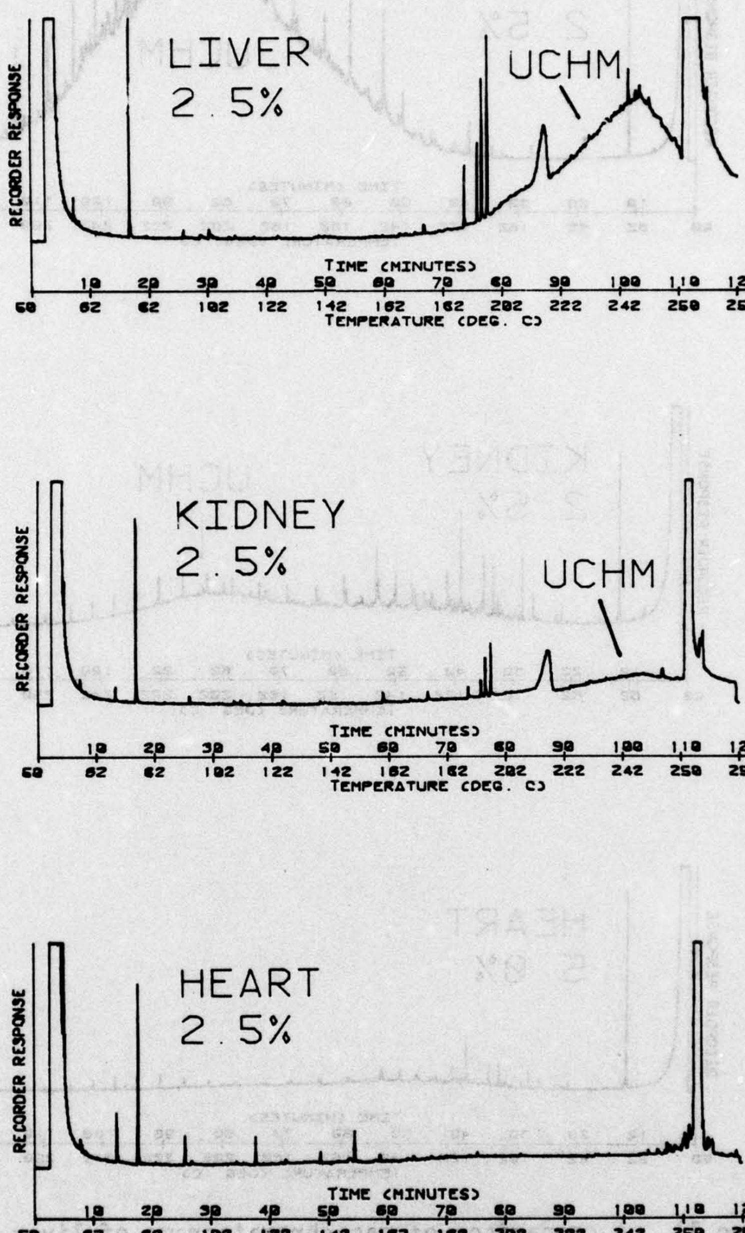

Figure 12. **A comparison of gas chromatograms of liver, kidney, and heart 2.5% treatment group saturate hydrocarbon fractions illustrating the presence of a high molecular weight aromatic UCHM in the liver and kidney, but not in the heart. The gas chromatographic conditions are described in Methods and Materials.**

PETROLEUM HYDROCARBONS IN ARCTIC RINGED SEALS, PHOCA HISPIDA, FOLLOWING EXPERIMENTAL OIL EXPOSURE

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ABSTRACT

Ringed seals, *Phoca hispida*, showed rapid absorption and clearing of hydrocarbons from Norman Wells crude oil in body tissues and fluids when exposed experimentally by immersion and ingestion. Measured fluorometrically, relatively low but significant levels were found in tissues, blood, and plasma following external exposure. Levels in bile and urine were higher, indicating these to be routes of excretion.

Analysis by gas chromatography of the crude oil used in the immersion experiment showed weathering effects, with a major loss of the more volatile fractions by 19 h of seawater surface exposure. Spectral scans of UV absorption and fluorescence of the oil showed characteristic patterns.

Ingestion of a ^{3}H-benzene and a ^{14}C-naphthalene labelled crude oil fed in fish resulted in high activity in blood, plasma, blubber, and liver. Activity of ^{14}C-naphthalene in urine was high, particularly for water soluble fractions as compared to hexane extracts, also indicating renal excretion. Only low concentrations of crude oil hydrocarbons were found in liver and kidney tissues following oil ingestion.

INTRODUCTION

Exploitation of arctic oil reserves is likely to be extensive, both in the western and eastern Arctic. The potential for oil spills is high, particularly for polar continental shelf reserves because of the hazardous conditions of production and shipping in arctic waters (Glaeser 1971). The environment itself enhances the problem in that cold temperatures retard volatilization of the light frac-

tions common to arctic petroleums. These fractions have been shown to have marked effects in many organisms and their effective toxicity will be enhanced (Barnett and Kontogiannis 1975, Morrow 1973, Ottway 1971). In addition, the presence of ice cover for a large part of the year may be expected to decrease volatilization of any oil trapped below the ice surface. Spilled oil would tend to concentrate in leads between ice-floes and in breathing holes used by marine mammals.

The effects of petroleum contamination on seals has been little studied, in spite of the fact that seals form an important part of the arctic food chain. The ringed seal, Phoca hispida, for example, has been shown to be a food source for polar bears (Stirling 1974) and arctic foxes (Smith 1976). Additionally, it forms an extensive resource for native peoples of the North. Cross-contamination from seal to human consumer must be considered, but is virtually impossible to assess because there is no information on petroleum hydrocarbon levels in seals following contact with oil. The ringed seal species also serves as an ideal model of contamination effects because it is widely distributed in the Arctic, showing a migratory habit and a preference for ice-cover (Smith 1973, Stirling et al. 1977).

In seals, exposure has been cited to cause eye irritation (Nelson-Smith 1970, Smith and Geraci 1975) and other damage (California Department of Fish and Game 1969, Lillie 1954, Spooner 1967). The Santa Barbara Channel oil spill has been suggested as the cause of mortalities in island colonies of california sea lions and northern elephant seals. However, Brownell and LeBoeuf (1971) interpreted these as natural mortalities. LeBoeuf (1971) also reported that elephant seal pups recovered from oil coating. Reports of exposure of arctic seals to spilled oil show that no related mortalities occurred following contact (Hess and Trobaugh 1970, Morris 1970, Muller-Willie 1974).

In this study, the uptake, distribution, and clearance of petroleum hydrocarbons was examined in the ringed seal following simulated oil spill and dietary exposure. The results reported here served in part to correlate with the observed toxic effects in seals, as well as to establish some parameters of oil uptake and retention as related to the mode of exposure and hydrocarbon characteristics.

MATERIALS AND METHODS

Ringed seals were captured at Brown's Harbour, on the east side of Cape Parry, N.W.T. (70°50'30"N, 124°22'30"W), in August through September of 1974 and 1977. The seals were caught by net as described in the method by Smith et al. (1973) and held in seawater in chain link fencing enclosures until the exposure experiments or shipment to the University of Guelph. They were fed arctic char during the holding period. Additional seals were shot and were used to establish baseline levels for hydrocarbon determinations in tissues and body fluids.

The contaminant oil used was a fresh Norman Wells crude oil, resembling a typical arctic continental shelf oil in being a light oil, high in concentration of low boiling point hydrocarbons. Exposure

to an oil spill was simulated experimentally by immersion of six seals for 24 h in seawater covered by a 1-cm-thick layer of petroleum. Samples of the contaminant oil on the water surface were taken during the exposure period for hydrocarbon analysis. After 24 h immersion, all six seals were transferred to clean seawater. The seals were killed at scheduled intervals for the week following their exposure to oil. Selected tissue samples, as well as blood, plasma, bile, and urine were taken for hydrocarbon analysis. The samples were packaged airtight in aluminum foil or glass and stored frozen until analysis.

A separate aspect of the oil uptake study was to examine the fate of the oil in the seals following ingestion exposure. Five ringed seals captured at Brown's Harbour in 1974 were taken to the University of Guelph where an ingestion study was carried out using ^3H-benzene labelled crude oil. The seals were fed herring containing embedded capsules of labelled Norman Wells crude oil at an oil dose of 1mCi/5ml/day for five consecutive days. Blood, plasma, and biopsy samples of liver, blubber and muscle (Engelhardt 1976) were taken at frequent intervals during and for 28 days after the ingestion period. These samples were analyzed for tracer activity. A second feeding study was carried out in 1977 at Brown's Harbour. In this case, four seals were fed 5 ml of Norman Wells crude oil per day for four consecutive days. The oil was labelled with ^{14}C-naphthalene at 5 µCi/5 ml and fed in arctic char. The seals were killed at the end of the dosing period and samples of blood, plasma, bile, and urine, as well as most body tissues, were taken to be analyzed for tracer activity and petroleum hydrocarbon concentration.

Aliquots of surface-slick oil samples taken during the oil immersion period were analyzed by gas chromatography on a support-coated open-tubular (SCOT) OV-1 column, temperature programmed at 4°/min from 60 to 275°C, and isothermal at 275°C. Aliquots of fresh Normal Wells crude oil and weathered oil samples were dissolved in hexane to characterize UV absorption and fluorescence spectra.

Extraction of petroleum hydrocarbons from tissues and fluids was carried out by steam distillation using the method of Ackman and Noble (1973). Characterization of petroleum hydrocarbons in hexane extracts of the tissue and fluid distillates was carried out by UV absorption spectrophotometry. The extracts were scanned and compared with the absorption pattern of Norman Wells crude oil over a wavelength range of 190-350 nm.

Quantification of petroleum hydrocarbons in sample extracts was carried out by fluorometry with excitation and emission wavelengths chosen in accordance with the spectrofluorescence scan of a Norman Wells crude oil standard. The amount of fluorescence in an experimental sample significantly above that of the mean fluorescence of six control samples was interpreted to be due to Norman Wells crude oil fractions, and was expressed as µg/g tissue or fluid wet weight.

Radiotracer analysis of tissues and fluids for ingested labelled hydrocarbon activity was by liquid scintillation counting. Samples containing ^3H-benzene, that is tissue biopsies and body fluids, were assayed for total ^3H activity by digestion of the sample following the methods of Hansen and Busch (1967). In the case of ^{14}C-naphthalene, the activity was determined in hexane extracts of the tissues and fluids of the treated seals. In addition, bile, plasma, and urine were assayed for ^{14}C activity in the water-soluble fraction

remaining after the hexane extraction using an emulsifier scintillation fluor.

RESULTS

Normal Wells crude oil showed peak absorption of the UV spectrum at 225 nm. The UV absorption peaks obtained from the fluids and tissues of the experimental seals coincided with those of the petroleum, while no such characteristic peaks were noted in samples of the control animals. The controls were then assumed to be free from petroleum contamination, at least within the sensitivity of the method used. In quantification, background fluorescence of the control samples was interpreted to be due to native compounds. A spectrofluorometric scan of the crude oil indicated a characteristic excitation peak at 325 nm and a fluorescence emission peak at 370 nm (Figure 1).

Comparisons by gas chromatography of fresh and weathered oil taken during the immersion period showed compositional changes, notably the losses of benzene and other low boiling point components (Figure 2). The UV absorption and fluorescence spectra showed no qualitative changes with weathering.

As a result of oil immersion, blubber, brain, muscle, kidney, and liver showed varying low concentrations of petroleum hydrocarbons with no significant pattern of change in concentration with time. Lung tissues showed only trace amounts in all seals (Table 1). The highest levels of hydrocarbons in the oil-immersed seals were found in the body fluids. Urine and bile had the highest concentrations, 39 and 58 μg/g, respectively, 2 days after oiling. Urine levels declined with time, while bile concentrations remained high.

Results from the ingestion study with ^{3}H-benzene labelled oil showed their highest tracer activity in the blood on the second day of dosing, with a sharp decline thereafter (Figure 3). The absolute activity in plasma was somewhat lower, but did not decline until after the 5-day dosing period. All tissues taken by biopsy during the ingestion experiment showed pronounced activity in the day 2 sample (Table 2); liver and blubber more than muscle. In all cases the activity was low by day 28.

Following ingestion of ^{14}C-naphthalene labelled oil, the activity in the hexane extract of the tissues was highest in the case of blubber, with generally low activities in adrenal, lung, and thyroid tissues, and essentially only trace levels in the other tissues examined (Table 3). Hexane extracts of the fluids indicated only the urine to have measurable ^{14}C-naphthalene activity. Examination of the ^{14}C activity left in the water-soluble phase of the extraction again showed only trace activity for bile, but high levels in plasma and particularly urine samples. In both of these latter cases, the activities were much greater in the water phase than in the hexane extract. Fluorometric measurement of petroleum hydrocarbons in hexane extracts of liver and kidney tissue distillates indicated only low concentrations in these two tissues (Table 4).

DISCUSSION

Weathering of the crude oil on the seawater surface effected compositional changes, particularly the loss of the more volatile fractions, including the benzenes, which are known to be acutely toxic (Moore and Dwyer 1974). It may then be expected that inhalation toxicity will decrease within even a few hours of weathering of the fresh spill on the open sea surface. The less volatile components which remain are also toxic, however, and are readily assimilated into tissues (Blumer et al. 1970, Stegeman and Teal 1973). The process of aging and weathering of crude oils in and on seawater has been well documented by Boylan and Tripp (1971), Smith and MacIntyre (1971), Erhardt and Blumer (1972), Harrison et al. (1975), and many others.

Overt effects of exposure to crude oil in ringed seals were minimal. Oil exposure by immersion resulted in transient problems of eye irritation, minor kidney damage, and sub-acute liver lesions. No effects on body core temperature were noted. Ingestion of the oil caused no significant lesions nor marked behavioral changes. The behavioral, physiological, and pathological effects of crude oil exposure in these ringed seals have been detailed by Smith and Geraci (1975) and Geraci and Smith (1976).

The ringed seal apparently shows a rapid absorption of petroleum hydrocarbons by both immersion and ingestion. Since there were no intestinal lesions nor presence of oil in the gut following immersion, it would seem that the uptake path was by way of skin or respiratory surface, or both. Ingested benzene and naphthalene appear to be readily taken into the body by way of the gut. Both of these two hydrocarbons accumulate to a high concentration in the blubber, while in a comparison of liver, the activity for benzene was much greater than that for naphthalene. Blubber and muscle levels of ^{14}C-naphthalene activity, however, were generally of the same order of magnitude as for ^{3}H-benzene, evident once a correction is made for the much lower specific activity of the naphthalene label.

Lower accumulated levels of petroleum hydrocarbons in tissues and blood than in bile or urine suggest biliary and renal routes of excretion. The latter site is supported by findings of mild renal tubular necrosis in at least one of the animals in this study. The existence of a detoxification mechanism is suggested also by the decrease in activity in blood in spite of continuing ingestion of the ^{3}H-benzene labelled oil. Detoxification is further supported by the low concentrations of petroleum hydrocarbons found in the hexane extracts of tissue distillates, particularly in the case of liver and kidney tissues following oil ingestion. In many species the liver is regarded as a principal site of detoxification and excretion of lipophilic substances, often through the action of microsomal enzymes (Hodgson 1974, Wiebel et al 1974). This organ appears to play a role in the ringed seal as well, as indicated by high total petroleum hydrocarbon levels in bile following immersion in oil. Surprisingly, bile showed only trace activity following ingestion of the ^{14}C-naphthalene labelled crude oil. It would appear that naphthalene in ringed seals is converted to a water-soluble form to be excreted by a renal route. This is evidenced by the high plasma and urine activities in the water phase of a hexane extraction, as compared to the organic solvent phase activity of the same samples. Unfortunately no urine

nor bile samples were available from the ^{3}H-benzene labelled crude oil ingestion experiment, so that it would be possible to differentiate the mode of benzene excretion in the seal. It is of interest here to note that both liver and kidney tissues in the ringed seal show aryl hydrocarbon hydroxylase activity, with kidney tissues in particular exhibiting enzyme induction following petroleum exposure (Engelhardt 1978).

The ringed seal serves as an appropriate model to examine and predict effects of oil pollution on marine mammals. The seal is likely to come into contact with oil in the event of a spill because of its obvious need to surface, most times in leads or through breathing holes in the ice which tend to accumulate the oil. Aside from coating the animal, inhalation toxicity is a problem. Inhalation toxicity due to the more volatile fractions may also be enhanced should the spill occur in the area of the subnivean birth lairs of the ringed seals. The lairs are enclosed and are entered by way of a breathing hole (Smith and Stirling 1975). The suggested vicarious use of air pockets under the ice on extended sub-ice travels (Bertram 1940, Milne 1974) may be another hazard since the pockets will tend to concentrate oil (Glaeser 1971) while not permitting evaporation. As in most seals, the ringed seal feeds on fish; fish have been shown to accumulate petroleum hydrocarbons (Connell et al. 1975, Korn et al. 1976, Lee et al. 1972, Pancirov and Brown 1977), which may then be ingested and further accumulated by the seal.

It has been shown in these studies that brief exposure to crude oil results in the short-term accumulation of petroleum hydrocarbons in ringed seal tissues and body fluids. Hepatic and renal detoxifying and excretory mechanisms appear to be stimulated by exposure to result in a rapid loss of the contaminant hydrocarbons from body tissues. The effects of longer exposures are not known, and may result in a greater tissue accumulation, particularly in blubber. The overall stress effect of oil dosing may be difficult to assess when it occurs as an event in itself, or else in conjunction with other external or internal stresses. It should be noted that when oil immersion was carried out in a captive colony of ringed seals, it resulted in the rapid death of all exposed animals (Geraci and Smith 1976), possibly the result of additive stress effects. Further, the ingestion of crude oil contaminated fish does appear to stress ringed seals since this resulted in a marked elevation of plasma cortisol levels (Engelhardt 1978). Thus, the results reported here must be regarded as being relevant to acute exposure and interpreted in the context of the experimental conditions. More prolonged or chronic exposures may have different effects.

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Table 1. Hydrocarbon concentrations in tissues and body fluids of six ringed seals, Phoca hispida, immersed in crude-oil-covered seawater for 24 hours

	Concentration (μg/g)					
	2 d		6 d			7 d
Sample	Seal 1	Seal 2	Seal 3	Seal 4	Seal 5	Seal 6
Blubber	2.3	4.0	3.2	1.0	1.0	0.6
Brain	2.3	2.3	0.8	0.6	0.6	1.0
Liver	1.2	1.4	-	2.5	0.5	8.4
Lung	T	T	T	T	T	T
Kidney	1.9	4.9	1.1	1.3	1.3	2.6
Skeletal muscle	T	14.3	3.6	T	T	T
Blood	4.7	11.6	3.1	8.0	1.6	T
Plasma	4.4	2.4	1.3	-	1.3	1.0
Bile	-	58.1	32.1	-	39.2	-
Urine	39.0	30.2	1.9	6.3	-	6.0

T = trace quantities; less than 0.5 μg/g

Table 2. Activity in ringed seal, <u>Phoca hispida</u>, tissue biopsies following dietary ingestion of labelled crude oil, lm Ci ^{3}H-benzene/5 ml oil/day for 5 consecutive days.

		Activity (dpmx10^4/g)		
Seal No.	Tissue	2d	16d	28d
7	blubber	0.65	0.14	-
	liver	9.77	1.07	-
	muscle	2.42	0	-
8	blubber	7.60	0.33	0.09
	liver	7.06	0.66	0.08
	muscle	1.72	0.55	0.43
9	blubber	7.95	0.08	0
	liver	2.58	0.38	0.14
	muscle	1.79	0.24	0.18
10	blubber	2.19	0	0.02
	liver	5.57	0.43	0.64
	muscle	1.53	0.14	0.18
11	blubber	6.22	-	-
	liver	6.82	-	-
	muscle	1.68	-	-

Table 3. Activity in ringed seal, Phoca hispida, tissues and body fluids following dietary ingestion of labelled crude oil, 5 μCi ^{14}C-naphthalene/5 ml oil/day for consecutive days (4 days seals 12 to 14, 2 days seal 15)

	Activity (dpm/g)			
Sample	Seal 12	Seal 13	Seal 14	Seal 15
Hexane-extracted fraction				
Adrenal	64	23	35	34
Blubber	470	450	782	280
Brain	22	T	T	29
Heart	T	25	T	T
Kidney	T	T	T	22
Liver	T	T	T	105
Lung	31	27	33	-
Lymph node	T	T	T	29
Pancreas	T	T	31	25
Skeletal muscle	T	T	T	42
Spleen	T	20	T	22
Thyroid	39	33	57	64
Blood	T	T	T	T
Plasma	T	T	T	T
Bile	T	-	T	T
Urine	300	66	100	109
Water-soluble fraction				
Plasma	2,052	1,369	1,277	-
Bile	T	-	T	T
Urine	63,450	59,259	-	17,141

T = trace quantities

Table 4. Hydrocarbon concentrations in liver and kidney tissues of four ringed seals, <u>Phoca hispida</u>, following dietary ingestion of crude oil, 5 ml oil/day for consecutive days (4 days seals 12 to 14, 2 days seal 15)

Tissue	Concentration (µg/g) Seal 12	Seal 13	Seal 14	Seal 15
Liver	T	1.1	0.7	T
Kidney	T	0.6	0.4	0.7

T = Trace quanitites; less than 0.3 µg/g

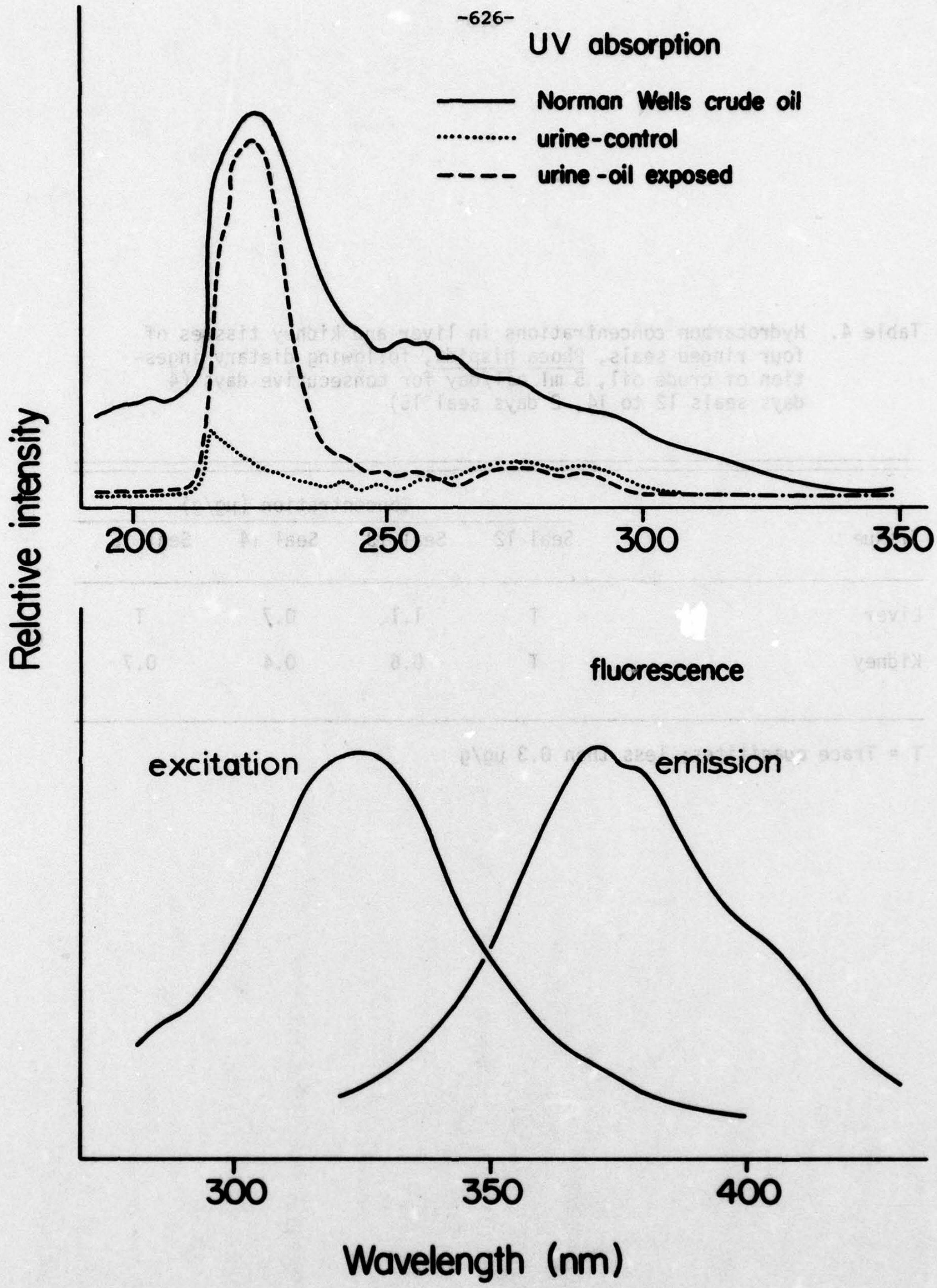

Figure 1. UV absorption and fluorescence spectra of Normal Wells crude oil.

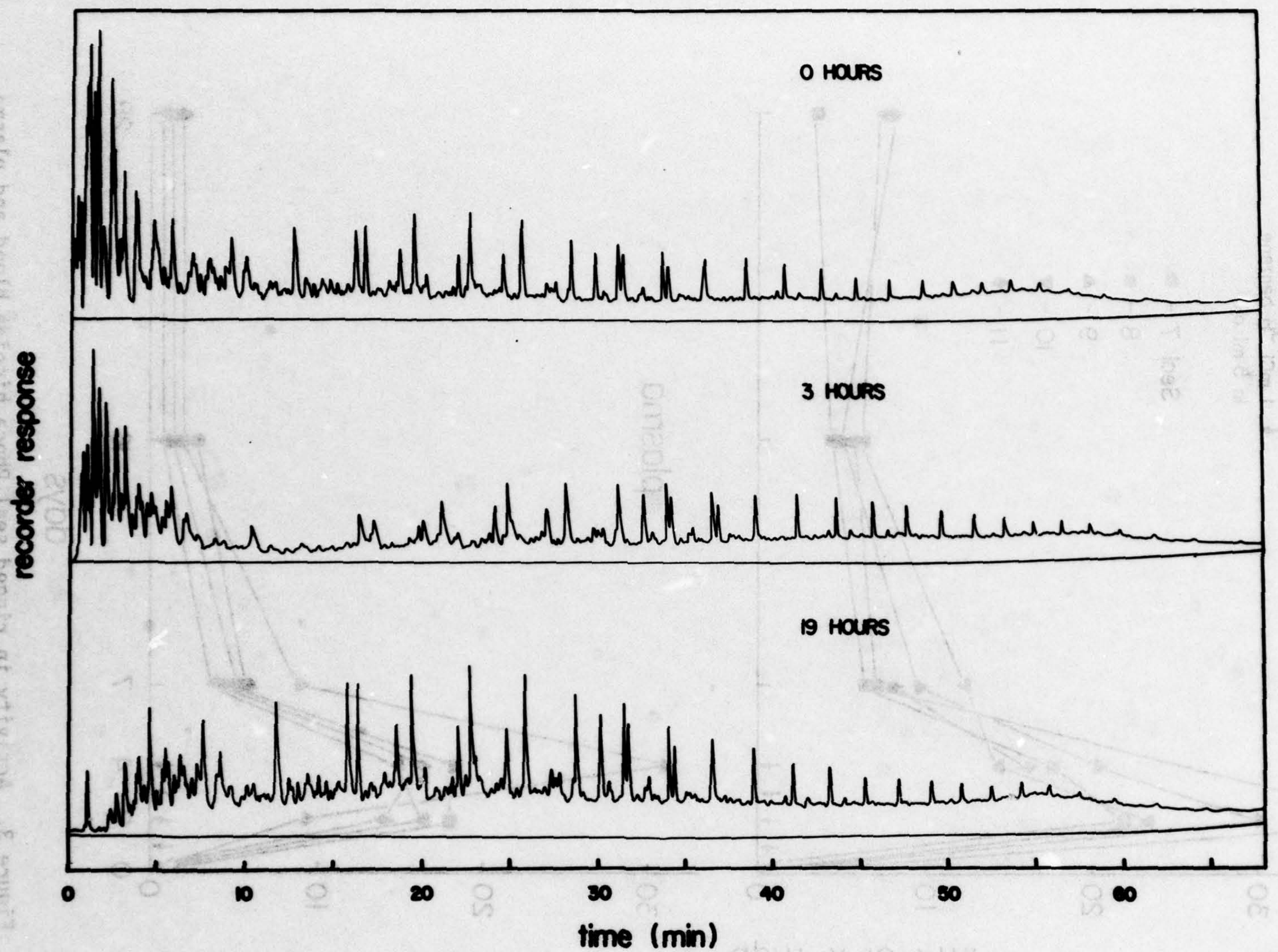

Figure 2. Characteristic gas chromatographic pattern of Norman Wells crude oil, examined fresh and after 3 and 19 hours of aging on sea water.

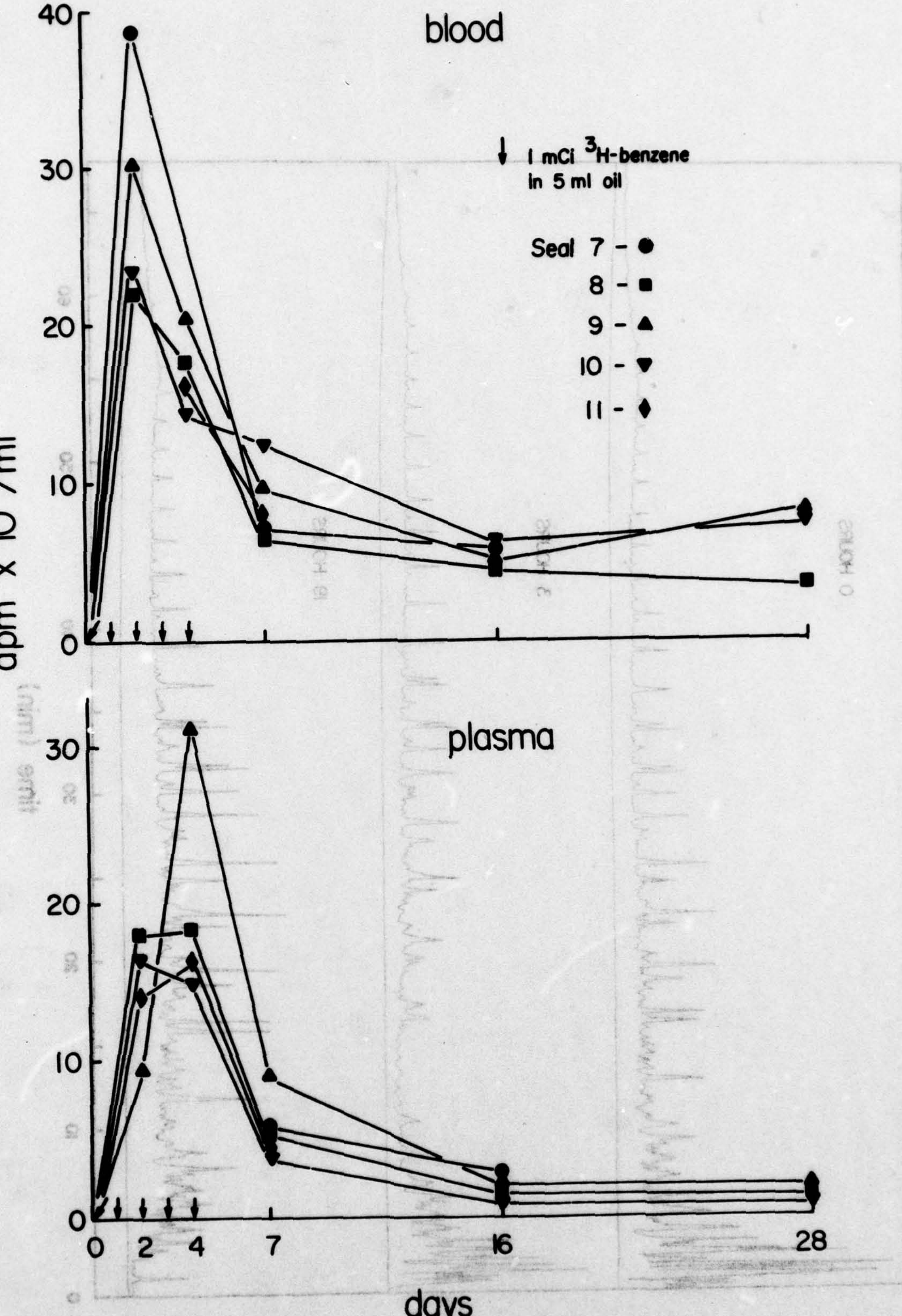

Figure 3. Activity in ringed seal *Phoca hispida* blood and plasma following dietary ingestion of labelled crude oil, 1 mCi ^{3}H-benzene/5 ml oil/day for 5 consecutive days.

DOES A PROBLEM EXIST RELATIVE TO SMALL SEA TURTLES AND OIL SPILLS?

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ABSTRACT

Evidence indicates that young green turtles are dispersed by ocean currents. These currents may also disperse oil spills, and some of the residue may float for as long as a year. Two small green turtles, one of which died, appear to have tried to eat tar balls and another small green turtle died after having been covered with liquid oil. There is a need to assess the impact of oil spills on the young of all species of sea turtles.

INTRODUCTION

In an effort to determine the feasibility of restoring depleted sea turtle populations the Florida Department of Natural Resources Marine Research Laboratory is studying the oceanic, survival, growth and dispersal of pen reared, yearling turtles. Primary emphasis is upon the green turtle, Chelonia mydas (Linnaeus), since the decline of this species can be more directly related to man's activities.

European colonization of the Americas saw the onset of the decline of this species (Carr, 1967; Parsons, 1962). The turtle was a readily available, desirable source of fresh meat for the crews of sailing vessels and colonists. As early as 1620,a decline was noted in the green turtle population of Bermuda, and protective legislation was enacted (Parsons, 1962). Over the intervening years many other areas adopted laws protecting sea turtles. However, population declines apparently continued.

Reasons for the continued declines are apparently varied, and probably include such things as: the inability of some jurisdictions to effectively enforce their laws; incidental captures of turtles during fishing operations designed to take other species, and;the loss of nesting beaches due to man's development of them for recreational, residential, or commercial use.

Because of the reported effects of petroleum on marine organisms (Parker, 1976), I became concerned with the possible effects of oil spills on sea turtles. Evidence indicates that young green turtles are dispersed by ocean currents (Witham, 1976; Witham and Futch, 1977). The

same currents that influence the dispersal of sea turtles can disperse oil spill residue, and some of the residue, in the form of tar balls, may float for as long as a year (Dedera, 1977).

OIL AND YOUNG TURTLES

To study the possible effects of oil on young sea turtles, some small green turtles were sent to a university by the Florida Department of Natural Resources. While this work indicated that behavioral changes occured after exposure to petroleum solutes, the results were not published. Evidence of harm to small sea turtles comes from three greens, two of which died, that were found on Florida east coast beaches. One turtle, number A4958, had been tagged by me and released at Key Biscayne, Dade County, Florida on 21 January 1976. When released, it had a carapace length of 10.2 cm. The turtle was found dead, with tar in its mouth, on Hutchinson Island, St. Lucie County, Florida on 9 February 1976. An untagged green turtle with a carapace length of 7.5 cm was found covered with oil on Hutchinson Island in mid-October of 1976. The animal was alive but in poor condition when it was taken to an aquarium. The external oil was removed and the turtle was put into an aquarium with other green turtles of about the same size. When the other turtles were fed, the one that had been covered with oil refused to eat. After being force fed, it began taking small amounts of food. It did not, however, resume full activity and it died on 9 November 1976. Dr. L. M. Ehrhart (pers. comm.) reported the taking of a somewhat larger green turtle, carapace length 31.8 cm, in the surf zone at the Merritt Island National Wildlife Refuge, Brevard County, Florida on 2 August 1977. When it was picked up, the turtle was upside down and disoriented. While being examined, the turtle was found to have tar in its mouth. It was taken to a laboratory, the tar was removed, and the turtle recovered.

DISCUSSION

The possibility exists that green sea turtles may be attracted by visual or chemical stimuli to petroleum at sea. They may die either as a result of trying to eat the congealed residue or from being covered with the liquid oil.

Since young sea turtles are so infrequently seen after leaving their natal beach that the period is called the "lost year" (Carr, 1967), young turtles dying as a result of oil spills would, most likely, also infrequently be seen. There is a need to study the effects of petroleum on the young of all species of sea turtles. It should not be assumed that because they are not often seen dead or dying as a result of having been in contact with oil that nothing serious is happening to them.

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EFFECTS OF SPILLS ON WATER COLUMN ORGANISMS

Chairman: GILLES LaROCHE
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SHORT TERM EFFECTS OF OIL ON PLANKTON
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ABSTRACT

A number of changes in plankton populations occurred after the addition of petroleum or its derivatives to CEPEX enclosures. These included increases in bacterioplankton, changes in the phytoplankton population, increases in numbers of rotifers and protozoans and decreases in ctenophores. Certain species of algae, particularly nanoflagellates and small-celled diatoms (less than 5 μ) appeared to be less susceptible to the effects of oil than larger-celled diatoms. Because of natural changes occurring in the phytoplankton population and variable effects of oil on these different populations it is difficult to predict the effects on plankton after an oil spill on ocean waters.

INTRODUCTION

The controlled ecosystem pollution experiments (CEPEX) were designed to determine the effects of pollutants on pelagic marine ecosystems. A series of papers have described the facility, results of replication experiments and the effects of adding copper, mercury, and petroleum (Azam et al. 1977; Beers et al. 1977; Lee et al. 1977; Menzel 1977; Menzel and Case 1977; Takahashi et al. 1976; Thomas et al. 1977).

We have added refined oils, crude oils and aromatic hydrocarbons to enclosures and examined the effects on the species composition and standing stocks of bacterioplankton, phytoplankton, microzooplankton and zooplankton. Petroleum and its derivatives were also added to water from control enclosures incubated in bioassay bottles. This report overviews the results of experiments carried out over 4 successive summers.

METHOD

Polyethylene enclosures (ca. 2 m diameter and 15 m deep) were filled with 60,000 liters of water from Saanich Inlet (British Columbia, Canada). The preparation of water extracts of fuel oil, crude oil or aromatic hydrocarbons and the method of addition has been described (Lee and Anderson 1977; Lee et al. 1977, 1978). Biological sampling was carried out at 2 or 3 day intervals both before and after oil addition. Chlorophyll a and nutrients (nitrate, phosphate and silicate) were measured on integrated water samples taken with a peristaltic pump from three depth intervals (0-5 m, 5-10 m and 10-13 m). Collecting, preservation and identification of phytoplankton, microzooplankton and zooplankton has been described (Beers et al. 1977; ~~Lee et~~ al. 1977; Takahashi et al. 1976; Thomas et al. 1977). For direct count of bacteria water samples preserved with Lugol's iodine solution were poured into a settling chamber, and were left for 48 hours at room temperature. Bacteria were counted in 20 fields randomly selected under an inverted microscope at 1000X.

Water samples were taken from the enclosures for bioassays of phytoplankton activity. The water was poured into one liter glass containers followed by addition of petroleum or petroleum derivatives and incubation in a lighted incubator at 10°C. Samples of the water were taken daily for measurement of the amount of chlorophyll and to enumerate the phytoplankton species. Chlorophyll a was measured by filtering 10 or 50 ml of water sample on a Millipore filter. The filters were then extracted with 10 ml of 90% acetone, and the fluorescence of the extract was measured with a Turner 111 fluorometer before and after acidification with 5% HCl (Strickland and Parsons 1972). For relative growth studies incubation was for 4 days followed by chlorophyll a measurements.

RESULTS

Bacterioplankton

The addition of petroleum or its derivatives resulted in large increases in bacterioplankton. This was particularly pronounced when naphthalenes were added to an enclosure. Immediately after the addition of these hydrocarbons there was a large increase in bacterial cells and after a few days aggregates or clumps of bacteria were noted throughout the water column (Figure 1). Naphthalenes were rapidly degraded in waters of treated enclosures (Figure 2) and some of the

increase in bacterial numbers may have been due to increases in hydrocarbon-degrading microbes. Hydrocarbons may also have effected the secretion of organics by phytoplankton which would in turn stimulate bacterial growth.

Nutrients were added every 4 days during the experiment. The rate of nitrate uptake in the hydrocarbon treated enclosures were generally twice that in the control enclosures. For example, in the summer of 1976 nitrate uptake averaged 3 μg-atoms N/liter/day in hydrocarbon-treated enclosures, whereas it averaged 1.5 μg-atom N/liter/day in the control enclosures. Rates of silicate uptake were the same in the treated and control enclosures. The explanation we offer for the difference is that hydrocarbon degrading bacteria took up nitrate but not silicate during their rapid increase in the treated enclosures.

The rate of microbial degradation of hydrocarbons was evaluated by adding ^{14}C-labeled hydrocarbons to water samples from the treated and control enclosures and measuring the $^{14}CO_2$ produced. As a result of adding Prudhoe crude oil to an enclosure, radiolabeled naphthalene and methylnaphthalene were degraded at rates of approximately 0.4 μg/liter/day (Figure 2; only the degradation of naphthalene is shown but very similar curves were obtained for methylnaphthalene). Water in the control enclosure showed an initial lag in the degradation of radiolabeled naphthalene and methylnaphthalene, but after incubation with the radiolabeled hydrocarbon for 72 hours the amount degraded was nearly the same as the maximum degradation observed in the oil treated enclosure. Higher weight aromatics, including fluorene, benz(a)anthracene, and benzo(a)pyrene, were not degraded in waters of either control or treated enclosures.

Phytoplankton

Petroleum studies were carried out in the summer when two major assemblages of phytoplankton are found in Saanich Inlet as described by Takahashi et al. (1977). Nutrient rich mixed waters, associated with summer blooms, are dominated by centric diatoms, generally species of Chaetaceros. A decrease in phytoplankton biomass occurs in the periods between summer blooms, when there is nutrient poor stratified water, with nanoflagellates and dinoflagellates the dominant phytoplankters.

The diatom, Ceratualina bergonii, rather than Chaetoceros spp., was the dominant phytoplankton in Saanich Inlet during the summer experiments of 1975 when fuel oil was added to one enclosure (Lee et al. 1977). Ceratualina was extremely sensitive to the effects of oil and a fuel oil hydrocarbon concentration of 40 μg/liter resulted in a decline of this diatom from 90% to less than 10% of the phytoplankton carbon. Nanoflagellates, particularly Chrysochromulina kappa, replaced Ceratualina as the major phytoplankter in the oil-treated enclosure. Ceratualina remained the dominant phytoplankter in the control enclosure. Addition of fuel oil at a concentration of 40 μg/liter to water from the control enclosure

in a bioassay bottle resulted in a *Ceratualina* decline and a subsequent increase in nanoflagellates. Thus, experiments in bioassay bottles reproduced the effects on phytoplankton observed in the enclosures. In the experiments of 1974 *Chrysochromulina kappa* briefly increased in an enclosure containing fuel oil at a concentration of approximately 20 μg/liter. Photosynthesis of a culture of *Chrysochromulina kappa*, isolated from this treated enclosure, was stimulated by addition of fuel oil (Parsons et al. 1976).

Naphthalenes, an important component of fuel oils, were added to one enclosure in 1976 to give an initial concentration of 75 μg/liter. In the summer of 1977 a dispersion of Prudhoe crude oil was added to an enclosure and the initial concentration of nonvolatile hydrocarbons was 280 μg/liter. These additions caused no marked effects on the phytoplankton populations which were dominated by species of *Chaetoceros*. To allow comparisons with the results of 1976, when fuel oil was added to an enclosure, different concentrations of fuel oil were added to water from the control enclosure and incubated in bioassay bottles (Figure 3). Fuel oil at a concentration of 50 μg/liter resulted in no phytoplankton changes. A concentration of 100 μg/liter caused a biomass decline for 4 days with a subsequent recovery so that the chlorophyll concentrations were similar to that in the control water 9 days after oil addition (Figure 3). After 9 days the fuel oil (100 μg/liter) treated water had small-celled (less than 5 μ) *Chaetoceros* spp. as the dominant phytoplankters, whereas in the control population and water with fuel oil at 50 μg/liter the dominant phytoplankton were large-celled (20 to 50 μ) *Chaetoceros* spp. Addition of methylnaphthalenes at concentrations of 50 to 75 μg/liter to control water in bioassay bottles did not change the quantity or quality of the phytoplankton population. Concentrations of crude oil (an API standard Louisiana crude oil) above 500 μg/liter showed effects similar to those observed for fuel oil at 100 μg/liter.

During the summer of 1976 the effects of fuel oil were studied on phytoplankton population before and after a bloom. Before a bloom, when flagellates dominated, there were no effects or possibly some stimulation of growth at concentrations below 100 μg/liter (Figure 4). After the bloom of *Chaetoceros* sp. very high fuel oil concentrations, above 300 μg/liter, were required to inhibit phytoplankton growth.

Microzooplankton

Important protozoans in the microzooplankton populations of the enclosures were ciliates of the orders *Oligotrichida* and *Tintinnida*. After additions of fuel oil to one enclosure in 1975 there were large increases in the tintinnid, *Helicostomella subulata*, and rotifers. These increases correlated with the decrease in the population of the centric diatom, *Ceratualina*, and the increases in nanoflagellates (Lee et al. 1977). Presumably, the rotifers and tintinnids fed on the nanoflagellates and bacteria which came up after oil addition. No differences were observed in numbers of naupliar copepods in treated and untreated enclosures.

In 1976 naphthalenes were added to one enclosure. Nanoflagellates did not increase. Instead centric diatoms, predominantly species of Chaetoceros, continued to dominate in both control and hydrocarbon-treated enclosures. Tintinnids, predominantly Helicostomella subulata, showed a marked increase in the hydrocarbon-treated enclosure (Figure 5). Rotifer numbers were the same in treated and untreated enclosures while naupliar copepods (Figure 6) decreased in the hydrocarbon-treated enclosure. The increase in the tintinnids after hydrocarbon additions appeared to correlate with the appearance of bacterial aggregates (Compare Figures 1 and 5). We hypothesize that the tintinnids were feeding on these bacterial aggregates. Presumably, rotifers were not able to feed on the bacterial aggregates.

Zooplankton

Acartia sp. and Pseudocalanus sp. were the dominant copepods during each of the controlled ecosystem experiments. No significant differences were noted in numbers of copepods in control and hydrocarbon-treated enclosures. Using fuel oil the 48-hour LD_{50} of the copepod, Calanus plumchrus, which occurs in Saanich Inlet was 1.4 mg hydrocarbon/liter. The concentration of fuel oil hydrocarbons added to one enclosure was 40 μg/liter. Heavy mortality of the ctenophore, Pleurobrachia pileus, occurred in hydrocarbon-treated enclosures. The 24-hour LD_{50} with fuel oil hydrocarbons for the ctenophore was 590 μg/liter. The naphthalenes in the fuel oil appeared to be responsible for this mortality (Lee and Anderson 1977). A review on the toxicity of oil to zooplankton has recently been completed by Corner (1978).

DISCUSSION

A number of changes in the plankton population occurred after the addition of petroleum or its derivatives to CEPEX enclosures. These included increases in bacterioplankton, changes in the phytoplankton population, increases in rotifers and protozoans and decreases in ctenophores. Increases in bacterial biomass after petroleum input to aquatic environments has been well documented (Atlas et al. 1976; Walker et al. 1975). Part of this increase is due to hydrocarbon-degrading bacteria. Increases in protozoans and rotifers after oil additions were correlated with increases in nanoflagellates and bacteria. In a freshwater lake the major food of rotifers were the nanoflagellate, Chrysochromulina parva (Edmondson 1965). In one CEPEX experiment the nanoflagellate, Chrysochromulina kappa, replaced a centric diatom species after fuel oil addition and a subsequent rotifer increase was noted (Lee et al. 1977). The protozoans which increased after oil additions were assumed to feed on bacterial aggregates or nanoflagellates which "bloomed" after oil addition.

Copepods appear to be effected only at high concentrations of hydrocarbons. The fuel oil 48-hour LD_{50} for the copepod, Pseudocalanus was 1.4 mg/liter (Lee and Anderson 1977). Exposure of the copepod, Eurytemora affinis, to fuel oil at high concentrations

(mg/liter) resulted in a reduction in the numbers of egg produced, mean brood size and rate of egg production (Berdugo et al. 1977). Exposure to lower concentrations of hydrocarbons produced no significant effect on feeding or reproduction. There was some indication of a slower growth rate for the copepod, Pseudocalanus, during exposure to fuel oil (40 μg/liter) in a CEPEX enclosure (Lee et al. 1977). Naupliar copepods decreased after addition of naphthalenes to an enclosure (Figure 6). Seawater suspensions of Kuwait crude oil did not effect the copepod, Tisbe bulbisetosa, with regards to numbers of eggs produced, hatching success, numbers of nauplii, or hatching success of third and fourth generation females (Venezia and Fossato 1977).

Several studies have shown effects of oil on the growth rate of marine phytoplankton (Gordon and Prouse 1973; Prouse et al. 1976; Pulich et al. 1974). Most of these studies were with pure cultures of algae. The effects included stimulation of growth at low hydrocarbon concentrations and inhibition at higher concentrations. The phases of algae growth include the lag period, exponential growth phase, stationary phase and a decline phase. Pollutants can effect length of the lag period, growth rate during exponential growth and final biomass reached at the stationary phase. Oil appears to effect the length of the lag period or growth rate rather than the final biomass (e.g., see Figure 3). In the CEPEX experiments with a mixed phytoplankton population the phytoplankton growth rate was altered and there were also changes in the structure of the population. It appeared that certain species, particularly nanoflagellates and small-celled diatoms, were more resistant to the effects of oil than large-celled centric diatoms.

Different species of algae differ with respect to a response to a particular pollutant with some algae able to develop resistance after long exposure to a pollutant (Stockner and Antia 1976). Phytoplankton in estuaries appear to be more resistant to organic pollutants than open ocean species (Fisher 1977). Preliminary studies with mixed phytoplankton from estuarine and inshore waters from coastal Georgia have shown that these phytoplankton are inhibited in their growth only at high concentrations (above 500 μg/liter) of fuel oil (Takahashi and Lee, unpublished data). Offshore phytoplankton were inhibited at lower concentrations. Pulich et al. (1974) observed inhibition of growth by the centric diatom, Thalassiosira pseudonana, when fuel oil concentrations were above 40 μg/liter. Higher concentrations of fuel oil were required to inhibit growth of various species of green and blue-green algae. In a fresh-water lake blue-green algae increased after crude oil addition (Hellebust et al. 1975; Snow and Scott 1975). Limitations of nutriens may effect phytoplankton growth or cause species shift after input of oil. In large oil spills the levels of nitrogen and phosphorus in the water limit the rate of microbial degradation of the oil (Colwell and Walker 1977). In the CEPEX enclosures nitrate uptake was much higher in hydrocarbon-treated enclosures than in control enclosures as a result of the increase in hydrocarbon-degrading microbes. Thus, in areas where nutrient concentrations are low phytoplankton would have to compete with microbes for nutrients after oil input.

Various blooms and declines of phytoplankton are a normal cycle in Saanich Inlet, as well as other ocean areas, during any one year (Takahashi et al. 1977). The species composition and nutrient concentrations are constantly changing with various species of flagellates and diatoms dominating at different periods. In addition to these seasonal changes are long term changes in the phytoplankton populations. For example, diatoms have declined drastically in abundance in the last decade in most areas of the north-eastern Atlantic Ocean, possibly due to changes in north Atlantic weather (Reid 1977). Any effects of oil would be superimposed over these various "natural" changes. The highly variable response of phytoplankton in our CEPEX enclosures to oil additions is probably due to very different type of populations present during any one experiment.

CONCLUSION

It should be kept in mind that even with large oil spills the concentration of hydrocarbons in the underlying water is low and this concentration decreases rapidly after the spill. In all of our CEPEX experiments there has been an exponential decrease of the hydrocarbon concentrations in the water (Lee and Anderson 1977; Lee et al. 1978). The hydrocarbons are removed from the water by such processes as biodegradation, volatilization and adsorption to suspended particulate matter. Thus with a single input of oil the plankton are only exposed to high concentrations of oil for a few days. Research is presently underway at the Marine Ecosystem Research Laboratory at the University of Rhode Island to study the effects on plankton which are chronically exposed to fuel oil (Vargo, G. 1978; Vargo, S. 1978). All of our experiments were on the order of 20 days or less so that recovery or permanent changes in the plankton populations were not observed.

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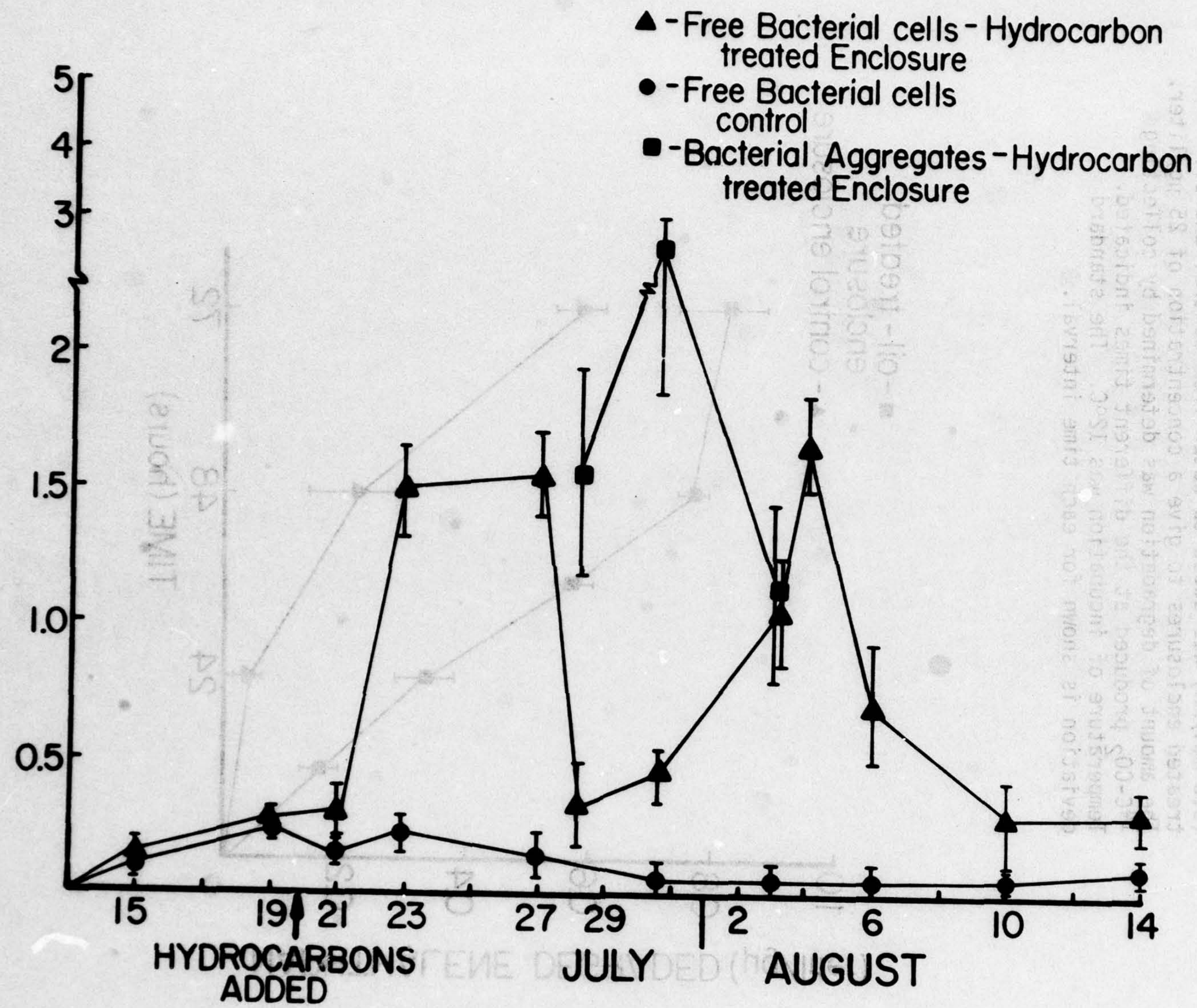


Figure 1. Changes in bacterial cell numbers after addition of naphthalenes (75 μg/liter - initial concentration).

Figure 2. Amounts of ^{14}C-naphthalene degraded with time in water from control and oil treated enclosure. A dispersion of Prudhoe crude oil (280 μg/liter - initial concentration) was added to the oil-treated enclosure 3 days before the degradation experiments were carried out. ^{14}C-naphthalene (3.6 mci/mM) was added to water from control and oil-treated enclosures to give a concentration of 25 μg/liter. The amount of degradation was determined by collecting $^{14}C\text{-}CO_2$ produced at the different times indicated. Temperature of incubation was 12°C. The standard deviation is shown for each time interval.

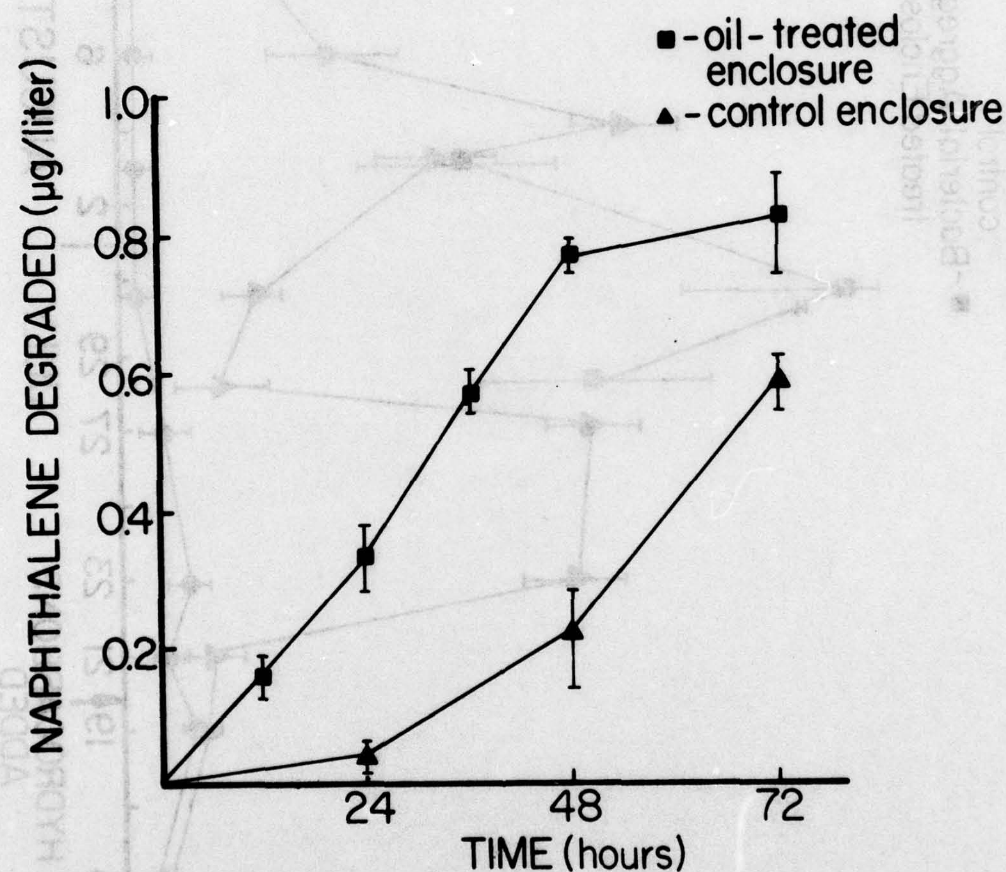


Figure 3. Bioassay experiment. Effects of different concentrations of fuel oil on phytoplankton, predominantly Chaetoceros sp., from a control enclosure.

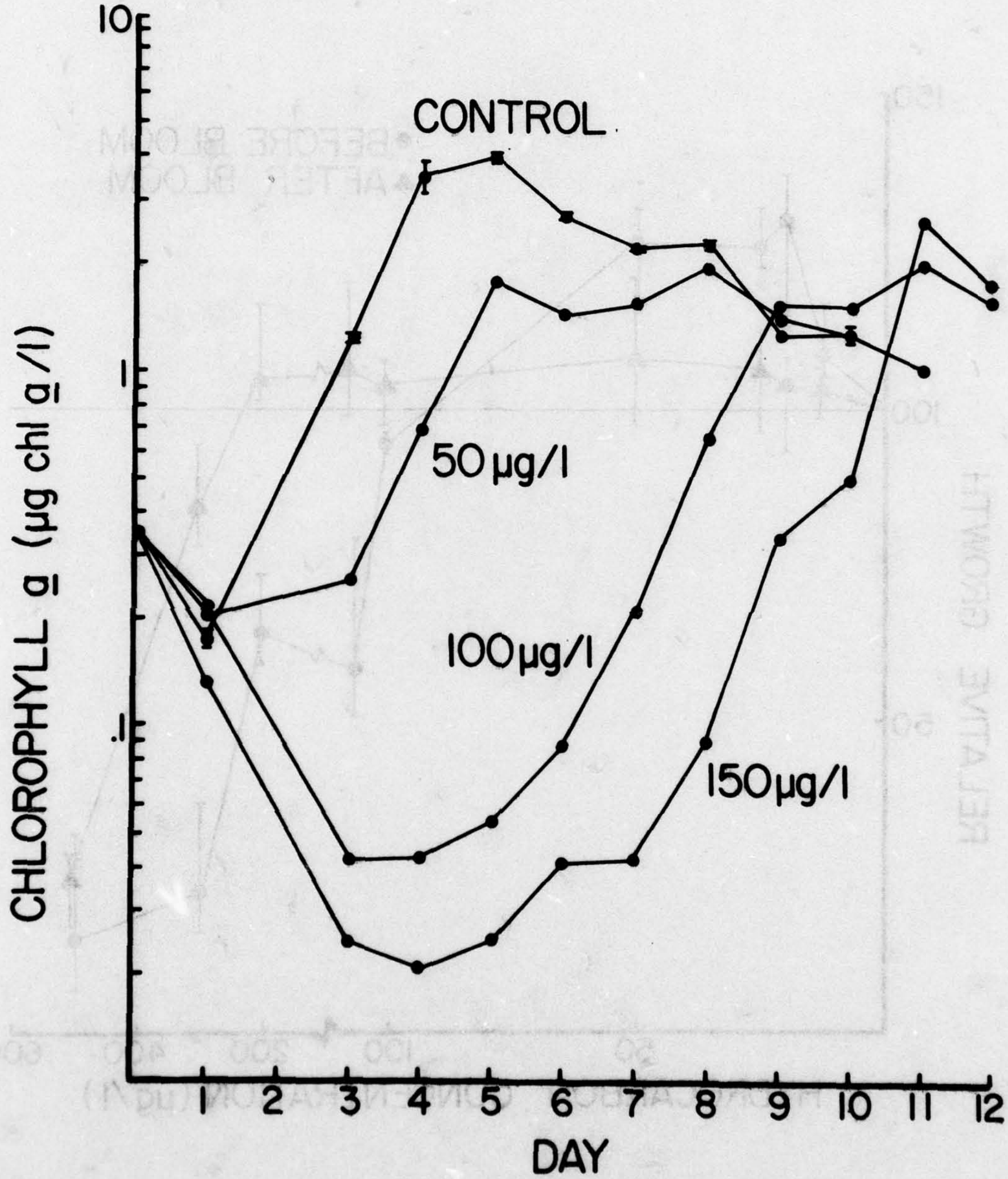
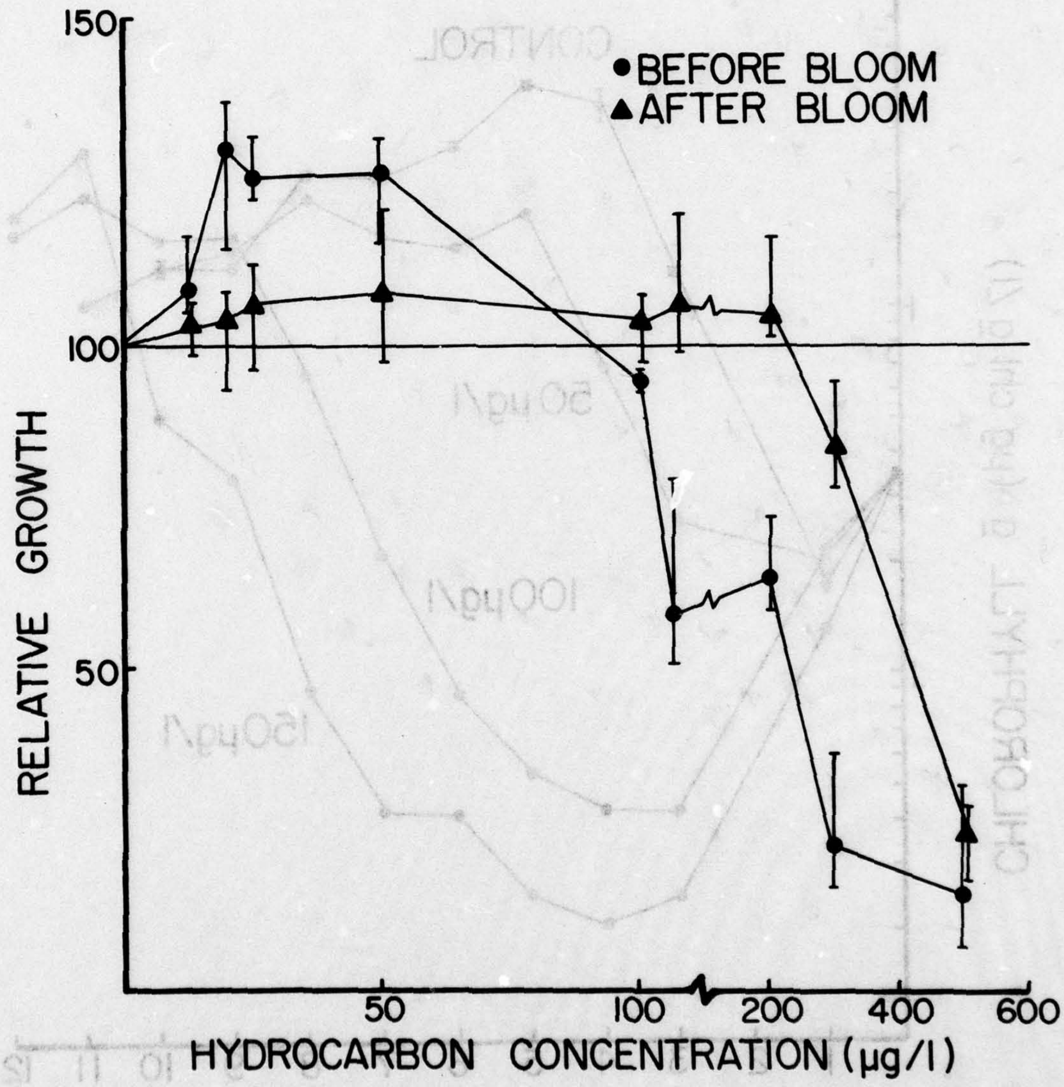


Figure 4. Effects of different concentrations of fuel oil before and after a phytoplankton bloom. Chlorophyll measurements in fuel oil treated water are given relative to chlorophyll in the control which is set at 100.



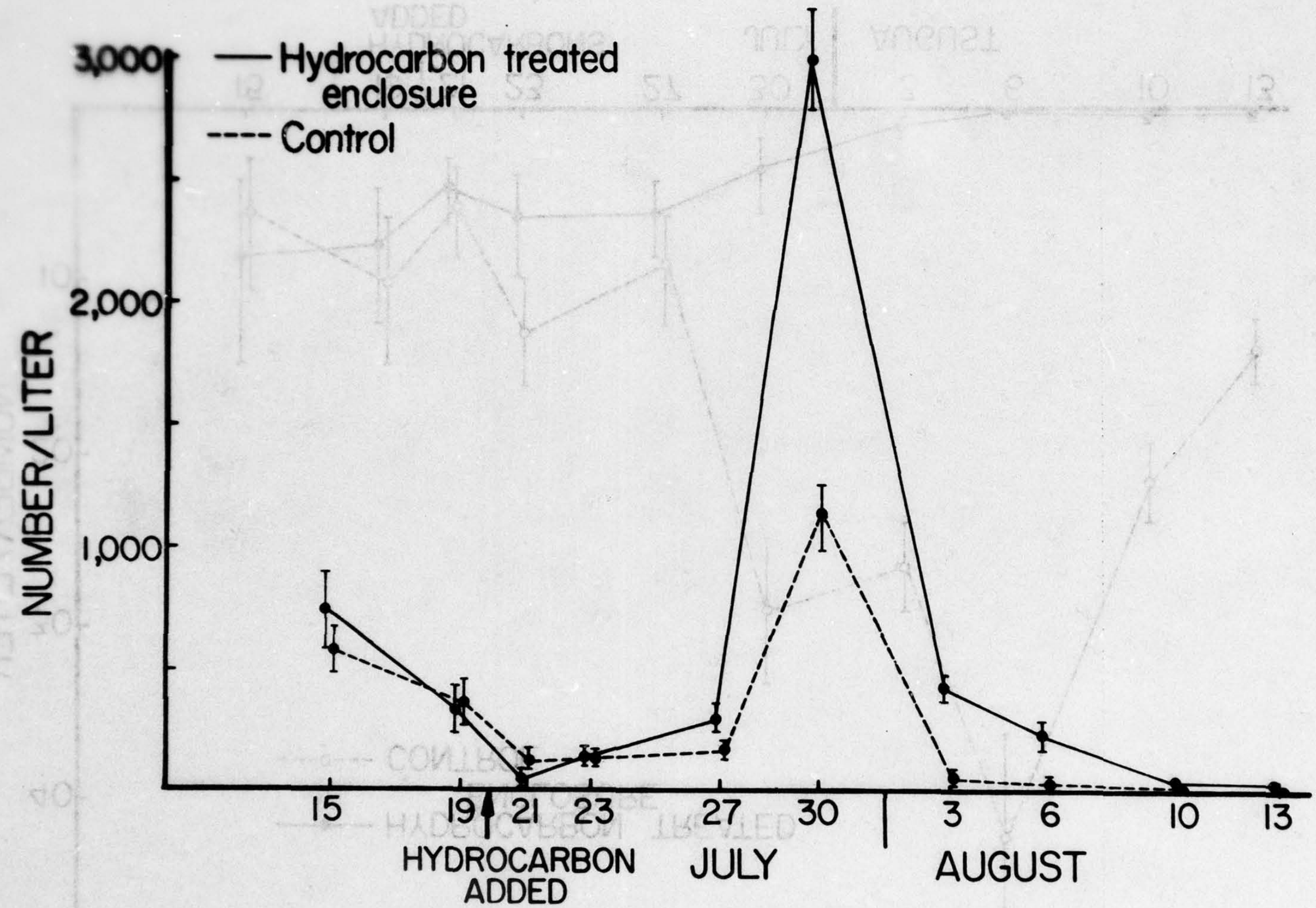


Figure 5. Changes in the numbers of tintinnids after addition of naphthalenes (75 µg/liter - initial concentration). The vertical bars indicate the confidence interval (95% level).

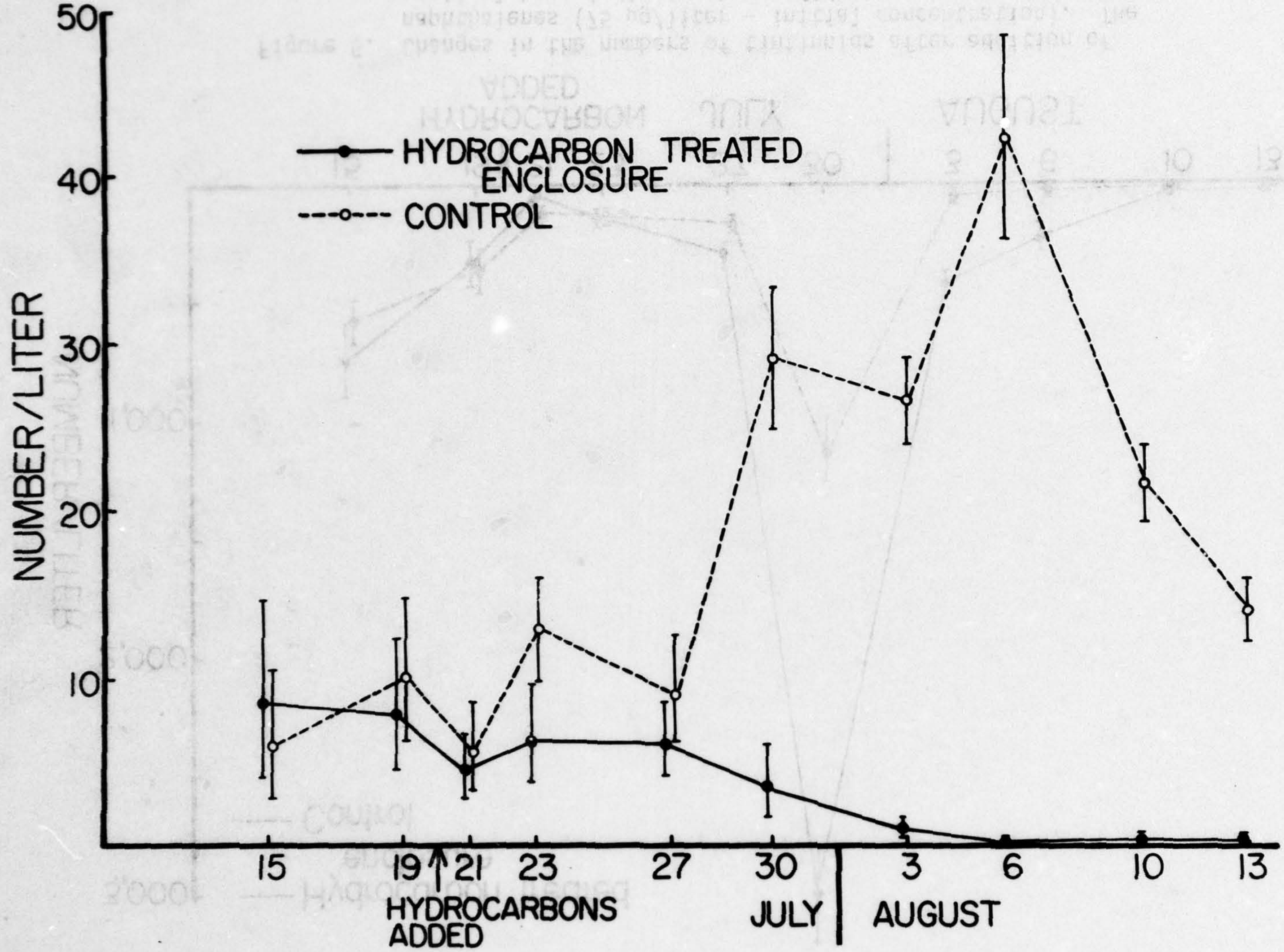


Figure 6. Changes in number of naupliar copepods after addition of naphthalenes (75 µg/liter - initial concentration). The vertical bars indicate the confidence interval (95% level).

CILIATES AS BIOINDICATORS OF OIL POLLUTION

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ABSTRACT

Oil uptake, toxicity, and community diversity experiments were conducted with members of the marine microfaunal community, primarily ciliate protozoa, in order to explore the possibility of using these organisms as biological indicators of oil pollution. *Euplotes diadaleos* ingests approximately 1 ng/min of emulsified crude oil over a three hour period. The 90 hr LC50 of crude oil to *Euplotes* is 1.7 ppm. The toxicity of crude oil is directly correlated with the log of the oil concentration between 0 and 74 ppm with one interesting exception: the population of *Euplotes* increases dramatically at 8 ppm. In field experiments, population, species number, and community diversity were monitored in artificial substrates in saltwater ponds experimentally treated with various crude oils. The oil descended through the water column and accumulated in the substrates as droplets bound to detritus and inorganic particles. The rate of descent is directly correlated with the salinity of the pond. Population and species number of the microfaunal community increased over pre-spill levels during the 21 days monitored except in the pond oiled with Nigerian crude oil.

INTRODUCTION

As part of it's oil pollution law enforcement responsibilities, the Coast Guard has final responsibility for clean-up of oil spills at the proposed Deepwater Ports in the Gulf of Mexico (U.S. Congress 1974). The Coast Guard Research and Development Center (CGR&DC) was therefore tasked with the investigation of potential methods for assessing the effectiveness of oil spill clean-up. One potential assessment system would use biological indicators of oil pollution.

Protozoa, particularly ciliate protozoa, may be effective bioindicators. Cairns (1974) lists numerous advantages to the use of protozoa as indicators of water quality. He describes a monitoring system employing protozoan communities colonizing easily-sampled artificial

substrates. Samples obtained from the substrates are analyzed for biological parameters that vary with water quality such as species composition and population.

Such a system may be useful for assessing oil pollution. Protozoan populations are affected by oil as demonstrated by the fact that blooms of ciliate protozoa have been noted after oil spills (Andrews and Floodgate 1974). The use of protozoa as oil pollution monitors has the additional advantage that the pollutant can be readily detected within the organism. Using fluorescence microscopy, Andrews and Floodgate (1974) were able to observe oil inside ciliates after exposure of the organisms to oil residues. An oil pollution bioindicator system employing protozoan communities in artificial substrates would therefore be useful since both biological and chemical parameters can be measured.

Our research has explored the possibility of developing such an assessment system. In laboratory studies we examined the rate of uptake of oil by a ciliate protozoan and measured the toxicity of oil to this organism. In field experiments we measured microfaunal community diversity and populations in artificial substrates moored in experimentally oiled saltwater ponds. During the course of these studies we have learned something about the passage of oil through the water column and the effect of this oil on microfauna. Despite a series of articles by Fenchel (1967, 1968, 1969) demonstrating the importance of protozoa to the ecology of the marine environment, few studies have addressed the effect of oil on these organisms.

The intent of this paper, then, is to present our results on oil uptake rates and oil toxicity to a marine ciliate protozoan. In addition, we will attempt to correlate these laboratory results with our field observations on the movement of oil through the water column and the effect of this movement of oil on the marine microfaunal community.

METHODS AND MATERIALS:

1. Measurement of Oil Content and Rate of Oil Uptake

The oil content of protozoans was measured using fluorescence microscopy. A Farrand Microscope Spectrum Analyzer (MSA) was attached to an Olympus Vanox research microscope equipped with a vertical fluorescence illuminator. This equipment is illustrated in Figure 1. The excitation filter allows the passage of ultraviolet light which causes oil to fluoresce. Fluorescent light passing the barrier filter is broken into a spectrum with a scanning monochrometer. A photomultiplier tube, photometer, and strip chart recorder produce a graph of the intensity of light over this spectrum. The characteristic spectral peaks for neat oils were determined and compared with the fluorescence spectra obtained from protozoa. If the spectra matched, it was assumed that the fluorescence exhibited by the protozoan was due to ingested oil. Since the height of the characteristic spectral peak is proportional to the amount of oil in the targeted area, the intensity of the fluorescence at the wavelength of this peak can be used as a measure of oil content once the instrument is calibrated for a particular oil.

The instrument is calibrated by using a thin prism of neat oil formed between two microscope slides separated at one end by a spacer of known thickness. As the oil prism is moved across the stage, the position of the targeted area and the intensity of the fluorescent light is noted. The amount of oil in the targeted area is calculated and correlated with the fluorescent light intensity. Thereafter, the intensity of fluorescent light at this wavelength is used as a measure of oil content.

The rate of uptake of Saudi Arabian light crude oil was measured for the marine ciliate protozoan Euplotes diadaleos. This organism was chosen because members of the genus Euplotes were reported by Andrews and Floodgate (1974) to ingest oil after exposure to oil residues. The particular species E. diadaleos (Diller and Koanaris 1966) is common locally in Groton, Connecticut, and is easily cultured. We selected Saudi Arabian crude oil since it is one of the principal crude oils to be offloaded at the Deep Water Ports.

Two milliliters of oil were emulsified in ten milliliters of ultrafiltered (.45 micron) seawater by stirring vigorously for five minutes with a vortex mixer. Several Euplotes were placed in this emulsion. Euplotes were then withdrawn from the emulsion one at a time, transferred through two ultrafiltered pools of seawater, and scanned with the MSA. The washing procedure was apparently effective since fluorescing areas were seen only within the organisms and not on their surfaces. To immobilize the organism during the scan, water was withdrawn from the preparation, pinning the organism between the slide and coverslip. The intensity of fluorescent light at 525 nanometers, the characteristic spectral peak for Saudi Arabian light crude, and the length of time the organism had been exposed to the oil emulsion were measured.

2. Toxicity Experiments

Pairs of Euplotes were placed in hanging-drop preparations of ultra-filtered seawater containing known concentrations of Empire Mix crude oil. We chose Empire Mix since it is another crude oil that will be handled at the Deepwater Ports. The hanging-drop preparations were made as described by Kudo (1966) with the exception that silicon rather than petroleum jelly was used as a sealant in order to avoid petroleum hydrocarbon contamination. The seawater-oil mixture was prepared by thoroughly shaking crude oil with ultra-filtered seawater in a separatory funnel and allowing the mixture to stand overnight. One liter of water with the solubilized fraction of oil was withdrawn and analyzed as described by Hiltabrand (1978). An additional aliquot of the test solution was used as stock for a dilution series from which the hanging-drop preparations were made. Five replicates were prepared for each concentration. The preparations were examined periodically and the number of surviving organisms recorded.

Three toxicity experiments were conducted. The first employed four concentrations of oil ranging from 0 to 74 ppm in order to obtain a broad view of the relation between oil concentration and toxicity to

Euplotes. The second experiment used six concentrations of oil ranging from 0 to 14 ppm in order to obtain a better understanding of toxicity at the lower end of the original range of concentrations. A third experiment was conducted to obtain a preliminary view of the effect of higher concentrations of oil presented as an emulsion. We employed three concentrations, 200, 100 and 50 ppm, of an emulsion made by ultra-sonification of oil and Oil Red O dye (Stainken 1975).

3. Community Diversity Experiments

In order to analyze the impact of oil on the microfaunal community of artificial substrates, we participated in a field experiment conducted by Mississippi State University. The experiment consisted essentially of oiling saltwater ponds and monitoring various biological, physical, and chemical parameters. Each pond is 30.5 meters in length and width and 2.1 meters deep. The microfaunal community was monitored by using polyurethane sponges as artificial substrates (Cairns 1974). Two sponges were deployed in each pond, one near the surface of the pond and one near the bottom. The sponges were moored to a weighted line buoyed by a float. Substrates were sampled by squeezing the interstitial water of each sponge into an eight-ounce glass jar. These samples were then placed in a cooler with ice and air-shipped to the CG R&D Center, Groton, Connecticut for analysis.

Three ponds were oiled on 12 April 1978, each with 22.6 liters of oil. One pond was oiled with Saudi Arabian Light crude, one with Nigerian crude, and one with Empire Mix. A fourth pond was left unoiled as a control. The substrates were sampled shortly before the spill, then one day, seven days, and twenty one days after the spill. Samples were examined for microfaunal populations using a Wild inverted microscope and enumerating the organisms contained in two milliliter aliquots of the sample. A Shannon-Weaver community diversity index was computed for each substrate (Odum 1971).

The samples of interstitial water were also analyzed for salinity, pH, and oil concentrations in order to ascertain whether the biological parameters could be correlated with these chemical parameters. Salinity was measured with a Beckman Solu-Bridge, pH was measured with a Colman Model 39 pH meter, and oil concentration was measured spectrafluorometrically (Hiltabrand 1978) using a Farrand Mark I fluorescence spectrophotometer.

Representatives of several taxa in each sample were examined for oil content by fluorescence microscopy. Three drops of sample, including detritus, were placed on a microscope slide and the organisms fixed with one drop of 1% copper sulfate. Oil content of organisms was determined by measuring the intensity of the fluorescent light at 520 nanometers while targeting a particular specimen.

RESULTS:

1. Oil Uptake

Oil is ingested by ciliates. This finding is illustrated by the fluorescence photomicrographs in Figure 2. The Euplotes in the top photograph had not been exposed to oil while the one in the lower photo-

graph had been exposed to an emulsion of oil in water for approximately one hour. Figure 3 compares the fluorescence spectra of the neat oil with that of a fluorescing vacuole in an oiled Euplotes.

Results of the rate-of-uptake experiment are shown in the graphs in Figure 4. The correlation coefficient for the intensity of fluorescence and the amount of time Euplotes was exposed to oil is .814. When the intensity of fluorescence is interpreted as quantity of oil, the slope of the line indicates that Euplotes ingests approximately one nanogram of oil per minute for the first three hours of exposure to the oil emulsion. The oil is ingested as droplets 4-6 microns in diameter which are enclosed in vacuoles. These vacuoles move about in the Euplotes in a clockwise fashion and are apparently expelled intact from the cytopynge. Since the fluorescence microscope lacks quartz optics and a variable excitation monochrometer, we could not determine whether the oil is significantly changed by the organism.

2. Toxicity

The initial toxicity test using four concentrations of Empire Mix crude oil from 0 to 74 ppm indicates a 90 hour LC50 of 1.7 ppm. Toxicity curves computed from the results are presented in Figure 5. The four data points are LC50s computed from regression lines of mortality against concentration (Sprague 1973). The bottom graph indicates a direct correlation between the log of the concentration of oil and the time it takes to cause 50% mortality. It further suggests, extrapolating beyond the data, that 1) even low concentrations of oil are eventually toxic, and 2) it would take an extremely high concentration of oil (22,000 ppm) to kill 50% of a population of Euplotes within 24 hours.

To test the prediction that even at low concentrations of oil, slight increases in concentration will lead to increased mortality, an additional toxicity experiment was conducted using six concentrations of oil between 0 and 14 ppm. The results of this experiment are presented in Figure 6. As indicated by this graph, Euplotes reproduced rapidly at the 8 ppm concentration of Empire crude oil. Both above and below this point in the range of concentration, increasing amounts of oil led to increased toxicity as had been seen in the earlier test.

To test the second prediction, that it would take an extremely large dose of oil to kill Euplotes in a short time, a third toxicity test was conducted using emulsions containing of 200, 100, and 50 ppm crude oil. The 200 and 100 ppm emulsions caused 80% mortality in less than 24 hours, which was not predicted. It must be noted, however, that the oil was presented as droplets, not the as the solubilized fraction used in the other two toxicity experiments.

During the course of these toxicity experiments we observed that Euplotes secretes mucus to which oil becomes bound. A mat of mucus and oil develops at the bottom of the hanging-drop and becomes colonized by bacteria.

It was also observed that the pollicle of Euplotes is apparently oleophobic. When an individual Euplotes rises to the surface of a hanging-drop preparation in the presence of surface oil, the oil moves a few microns away from the pellicle as if repelled.

3. Microfaunal Community Experiments

The results of the pond microfaunal community experiments are shown in Figures 7-11. Figure 7 shows the course of the oil concentration through the experiment as sampled from the sponges.

Figure 7 can be interpreted as an indication of the passage of oil down the water column. One week after the spill the top sponges contained the greater amount of oil while three weeks after the spill the bottom sponges contained most of the oil. The concentration of oil in the bottom sponges twenty-one days after the spill is an indication of the settling rate of the oil. This settling rate is directly correlated with the salinity of the ponds, as shown in Table 1.

Table 1

Correlation of oil concentration in the bottom sponge 21 days post-spill with the average salinity of the ponds

Pond	Oil Concentration (ppb)	Salinity
Nigerian	949	10.1
Saudi Arabian	442	8.9
Empire Mix	135	8.2

Correlation coefficient r = .99995

When the samples taken on day seven were examined with the fluorescence microscope, large amounts of oil could be seen associted with the detritus, as can be seen in Figure 12. Small droplets of oil 4-10 microns in diameter were embedded in organic detritus while many apparently inorganic particles were observed coated with oil.

A steep drop in population, species number, and community diversity occured on the day after the spill as can be seen in Figures 8-11. Since this drop occured in the control pond as well as the oiled ponds, it was probably due to the fact that the sponges had been emptied on the previous day for the pre-spill samples.

In the three weeks after the spill, the biological parameters in the control pond returned to pre-spill levels (Figure 8), while in the oiled ponds these parameters behaved differently, though not consistently

(Figures 8-11). The percent difference in the values of those parameters between pre-spill and 21-days post-spill are presented in Table 2.

Table 2

Percent change in biological parameters from pre-spill to 21 days post-spill. N = total population; S = number of species; H = Shannon-Weaver community diversity index.

Oil	Top N	Top S	Top H	Bottom N	Bottom S	Bottom H
Control	5.2	0.0	-6.3	-1.1	0.0	13.4
Saudi Arabian	650.0	62.5	-12.0	720.0	160.0	35.8
Nigerian	-13.6	27.3	-0.5	-100.0	-100.0	-100.0
Empire	513.3	183.3	56.2	327.5	220.0	105.4

The Saudi-Arabian-Crude-oiled pond and the Empire-Mix-crude-oiled pond show substantial increases in most parameters while the pond oiled with Nigerian crude was the most negatively affected.

To some extent the behavior of the biological parameters can be correlated with the concentration of oil in the sponges. The correlation coefficients are presented in Table 3.

Table 3

Correlation between oil concentration and biological parameters. N = total population; S = number of species; H = Shannon-Weaver community diversity index; the numbers given are the correlation coefficients, r.

Oil	Top N	Top S	Top H	Bottom N	Bottom S	Bottom H
Control	.840	.647	.747	.227	-.305	-.043
Saudi Arabian	-.642	-.581	.053	-.957	-.987	-.906
Nigerian	-	-	-	-.199	-.215	-.117
Empire	-.012	-.789	-.776	-.999	-.953	-.997

Figures are not given for the top sponge in the Nigerian-crude-oiled pond since inadvertently a pre-spill sample was not taken. Note the strong negative correlations for the bottom sponges. The Nigerian-crude-oiled pond does not show this strong correlation, but it must be kept in mind that the values of all biological parameters in this substrate were reduced to zero within three weeks.

DISCUSSION

Three defense mechanisms were exhibited by Euplotes during the uptake and toxicity experiments. One mechanism is the secretion of mucus which apparently binds oil and removes it from the water column. The secretion of mucus is a nearly universal biological response to irritation and has frequently been observed as a response to oil (Nelson-Smith 1973). The second mechanism is the possession of an apparently oleophobic pellicle. The third mechanism is the enclosure of ingested oil droplets in vacuoles which are moved to the cytopynge and expelled. The first two defenses prevent the entrance of oil into the cell while the third defense deals with oil once it has entered the cell. The latter defense apparently is not completely effective. Euplotes ingests oil droplets suspended the water column at the rate of one nanogram per minute, but such emulsions are highly toxic to the organism. The first two defenses, however, may explain Euplotes' ability to survive relatively high concentrations of solubilized oil for 24 to 48 hours. Apparently, the oil is prevented from entering the cell. With time, however, even a low concentration of solubilized oil increases mortality. Bacterial activity may be the cause of this breech of Euplotes' defences. Bacteria sequester oil in their cytoplasm (Lee 1976). If bacteria colonizing the mucus-oil mat in the bottom of the hanging-drop preparation are ingested by Euplotes, then during the process of digesting the bacteria, the ciliate would be exposed to the petroleum toxicants. Axenic studies will be necessary to test this hypothesis.

The role of mucus as a defense mechanism and as an oil-binder is intriguing. The role of oil-mucus binding in the uptake or rejection of oil by Mya arenaria and the negative implications of this mechanism for the environment are discussed by Stainken (1975). There is also the possibility, however, that mucopolysaccharides may be used as the basis of a product which could pass through the water column like a net, sweeping out toxicants as it seems to do in the hanging-drop preparations.

Our toxicity experiments show two exceptions to the general rule of increasing toxicity with increasing concentration of oil. One exception is that at about 8 ppm the population of Euplotes increases dramatically. This fact may correlate with the observation of blooms of ciliates a few days after spills (Andrews and Floodgate 1974). At the risk of invoking the same explanation for both toxicity and blooms, we again suggest that the intermediary is bacteria. Euplotes feeds on bacteria while bacteria feed on both oil and mucus. At some value of mucus and oil concentrations, the population of bacteria may be more stimulating to reproduction of Euplotes than the concentration of oil in the bacteria is toxic. The nature of this stimulation may be

merely the increase in the population of bacteria (Andrews and Floodgate 1974) or it may involve the bacterial production of a "conditioning vitamin" as has been shown in several protozoological studies (Manwell 1968). Again, axenic studies will be needed to test this hypothesis.

Another exception to the general rule of increasing toxicity with increasing concentration was found with the emulsion experiment. It was predicted that it would take approximately 22,000 ppm of solubilized oil to kill half the Euplotes population in a single day. One hundred ppm of oil in the form of small droplets, however, killed 80% within 24 hours. Thus, contrary to the conclusion of Rice, et al. (1977), the toxicity of dispersed droplets may be greater than the toxicity of soluble aromatics for Euplotes.

In the pond experiments, however, it was seen that such droplets may not be available to microfauna. The droplets are bound to detritus and inorganic particles, possibly by mucus. The binding of oil droplets to detritus, however, may increase the availability of the oil to bacteria since it associates the oil with the surfaces where most marine bacteria are found. The oil, mucus, and bacteria may interact to affect the microfaunal population in the manner postulated to explain the toxicity results.

Figure 13 shows a postulated relationship between oil concentration and biological parameters through time. As the oil descends through the water column, associated with detritus, its concentration builds up rapidly in the substrate, then is gradually reduced, possibly by biodegredation or bioturbation causing the ejection of contaminated detritus. The community may be affected by the initial increase in concentration, or may not, depending on the defense mechanisms of its members. As the oil concentration decreases, it passes the critical stimulating value, perhaps 8 ppm of solubilized oil. As the oil concentration passes this value, the biological parameters increase. The results presented in Table 3 of the correlation between oil concentration and biological parameters may be explained by when in the course of this interaction the samples are taken. The top substrate experienced an early increase in oil concentration compared with the bottom sponges. Consequently the samples taken from the top substrates are later in the cycle than those taken from the bottom substrate. The postulated timing of these samples is shown in Figure 13. As in the actual results in Table 3, the correlation coefficients between oil concentration and biological parameters for this postulated sampling scheme would be weakly negative for the top substrates and strongly negative for the bottom.

Figure 13b indicates a postulated interaction of oil and biological parameters over time in the Nigerian bottom substrate. Here the oil concentration may have failed to decrease to the "critical value" within the time that the microorganisms could resist oil.

It should also be noted that the Nigerian-crude-oiled pond was the most adversely affected. This result supports the conclusion of Brown (1976) who reported Nigerian to be the most toxic of the crude oils he tested.

CONCLUSIONS

1. Oil is ingested by ciliates. The rate of uptake of an emulsion of crude oil is approximately one nanogram per minute.

2. Oil is toxic to ciliates. Emulsions may be more toxic than the solubilized fraction of oil. The 90 hour LC50 of the solubilized fraction of Empire Mix crude oil to Euplotes diadaleos is 1.7 ppm.

3. Euplotes has defense mechanisms against oil including the secretion of mucus, the possession of an oleophobic pellicle, and the sequestering of oil into vacuoles which are then expelled. The process of breeching these defenses and causing toxicity may involve bacteria.

4. At a concentration of 8 ppm of Empire Mix crude oil, Euplotes is stimulated to reproduce. This stimulation may again involve bacteria and may be correlated with the observations of blooms of ciliates after oil spills.

5. The use of sponges as artificial substrates allows the observation of the passage of oil through the water column and the effect of this passage on microfauna. The oil in the water column appears to be primarily in the form of droplets embedded in detritus. The rate of descent of the oil through the water column apparently is dependent on the salinity of the water.

6. The passage of this oil through a substrate may cause the value of the biological parameters of the microfaunal community to increase, or the values may be reduced to zero. The difference in behavior of these parameters may depend on the oil concentration decreasing to a critical, stimulating value within the time the microfauna are able to resist the oil.

7. We think the results to date support the concept of using protozoa as bioindicators. The pollutant can be detected and, to some extent, fingerprinted, within the organism. The amount of oil in the organism can probably be related to concentration and time of exposure. Finally, the biological parameters of the community can be correlated with oil concentration, although the correlation is not simple.

ACKNOWLEDGEMENTS:

The authors wish to thank Dr. Doug Minchew at Mississippi State University for suggesting our participation in the oiled-pond experiments and then carrying out the deployment and sampling of the substrates. Many suggestions and constructive criticism were received during the course of this research from Dr. Thomas Sawyer of the National Marine Fisheries Service Laboratory, Oxford, Maryland and from Dr. Larry Frankel of the University of Connecticut. Advice on chemical techniques was received from Drs. Robert R. Hiltabrand, Alan Bentz, and Delyle Eastwood, Chemistry Branch, USCG R&D Center. Much of the laboratory work was done in an earnest and expert fashion by MST2 Robert Fortin, USCG.

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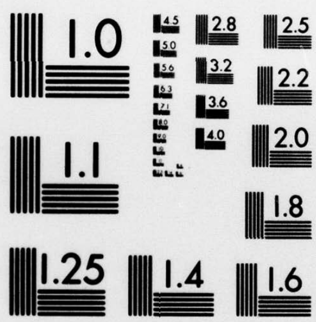
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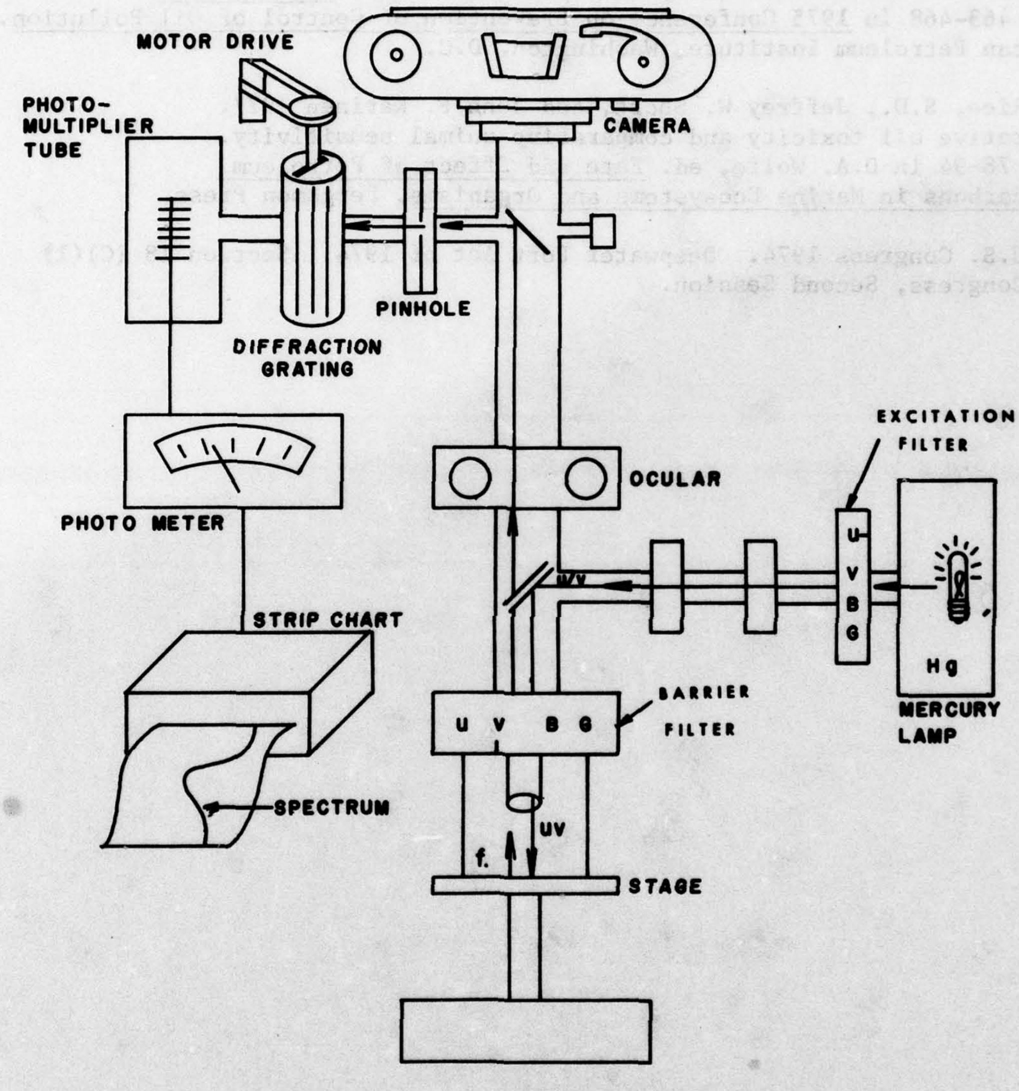


FIGURE 1 MICROSCOPE FLUORESCENCE SPECTRUM ANALYZER

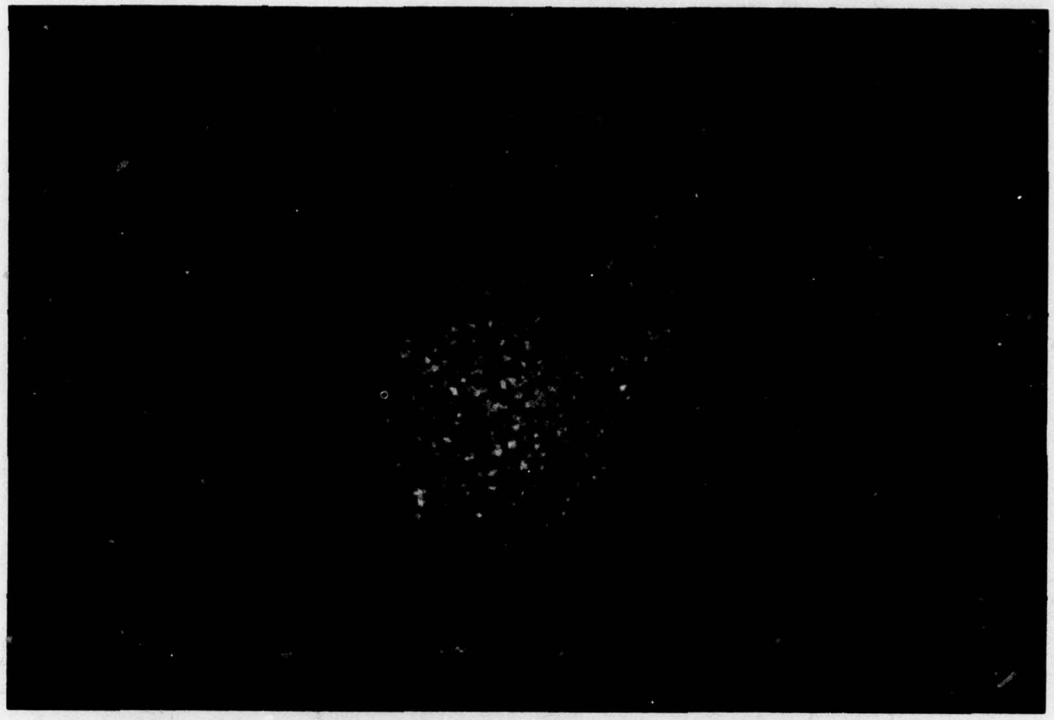


Figure 2a

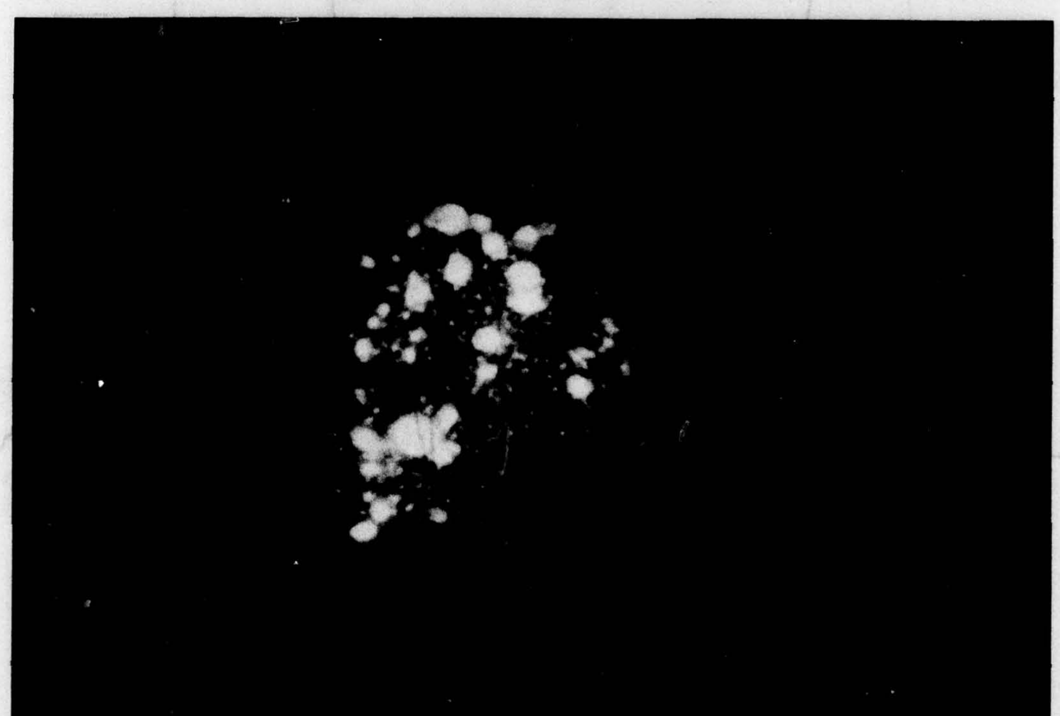


Figure 2b

Figure 2. Fluorescence photomicrographs of unoiled (top) and oiled (bottom) *Euplotes*. 400X.

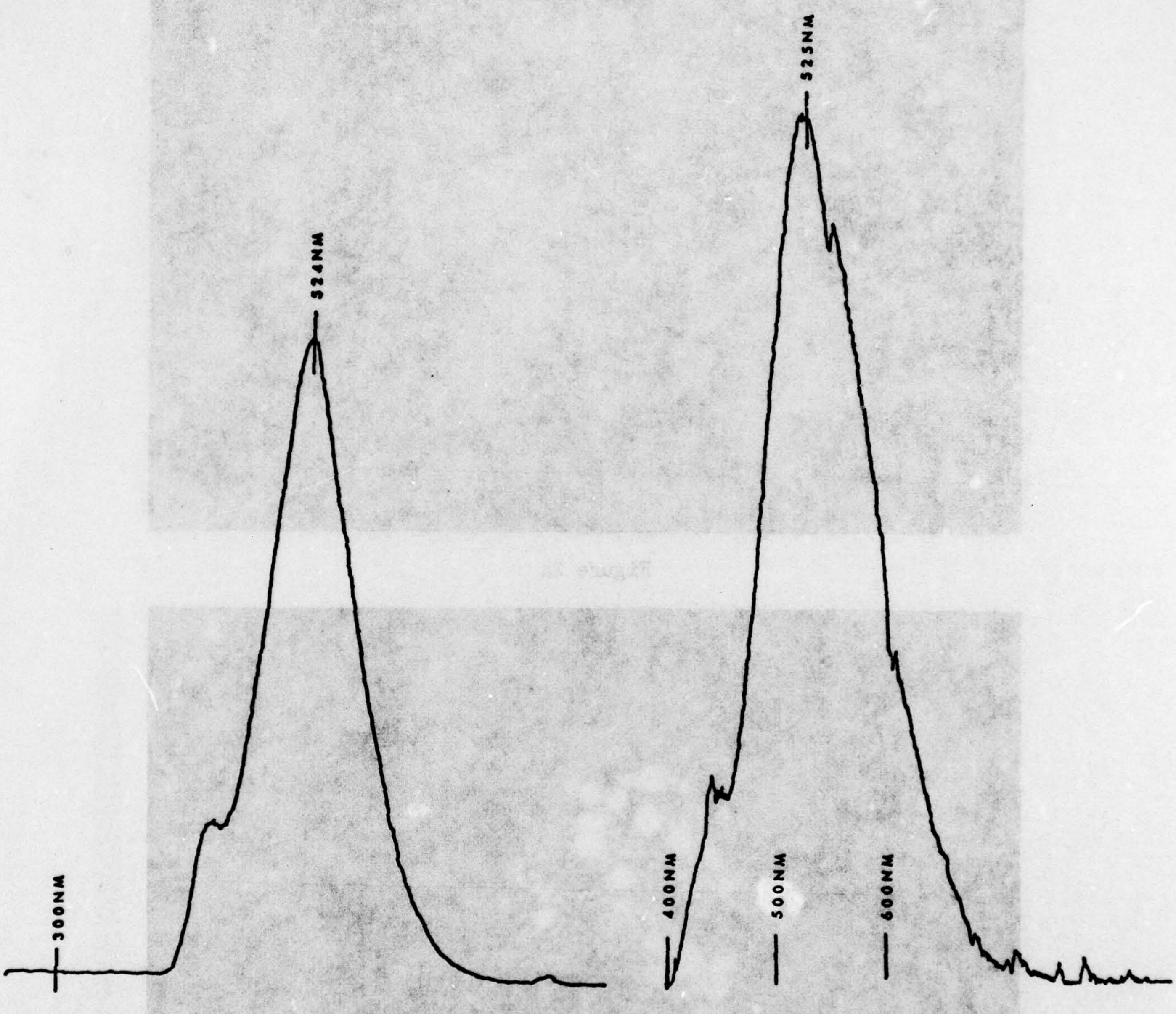
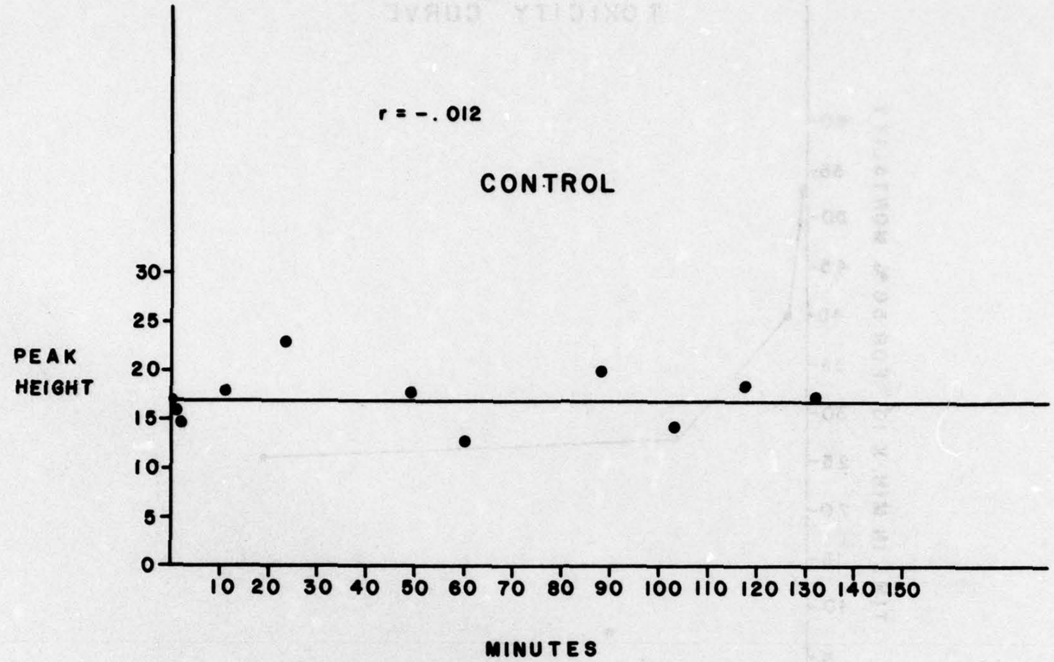


FIGURE 3. Comparison of spectra of neat Saudi Arabian light crude oil (left) and a fluorescing vacuole in the Euplotes which had been exposed to an emulsion of Saudi Arabian light crude oil. The differences in height are due to differences in both concentration and range settings.



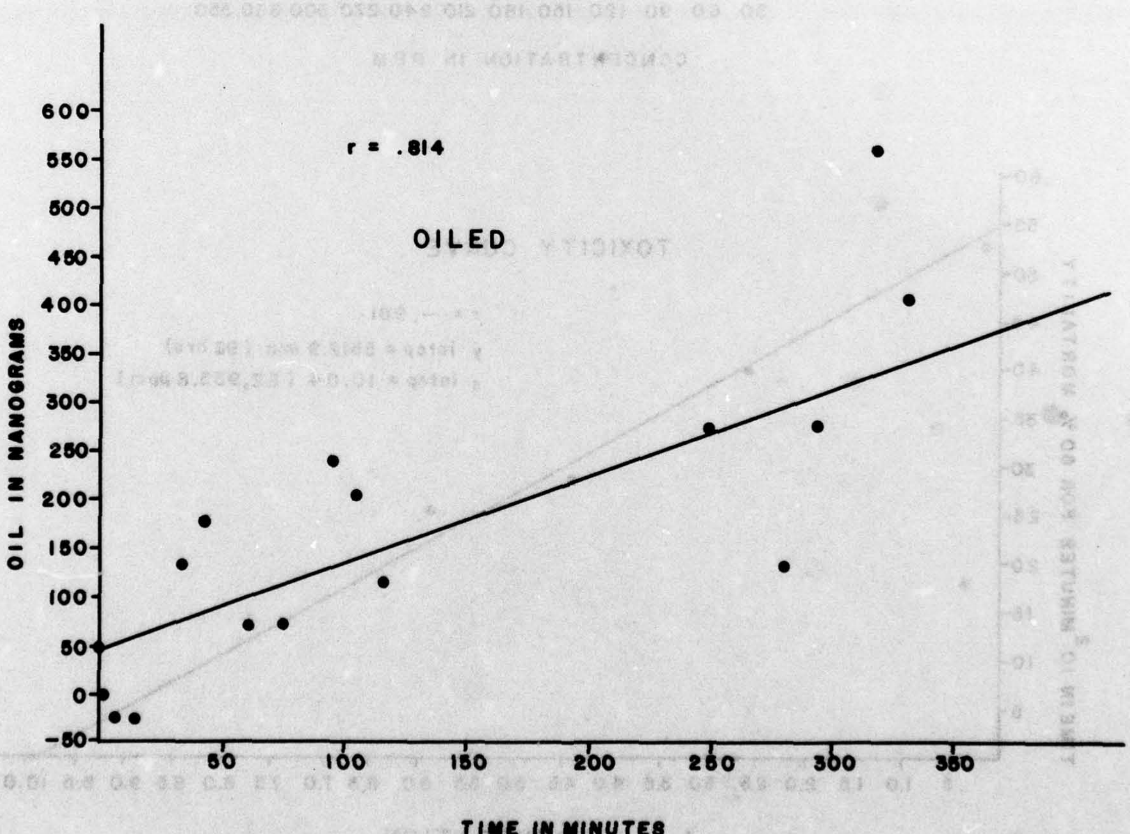
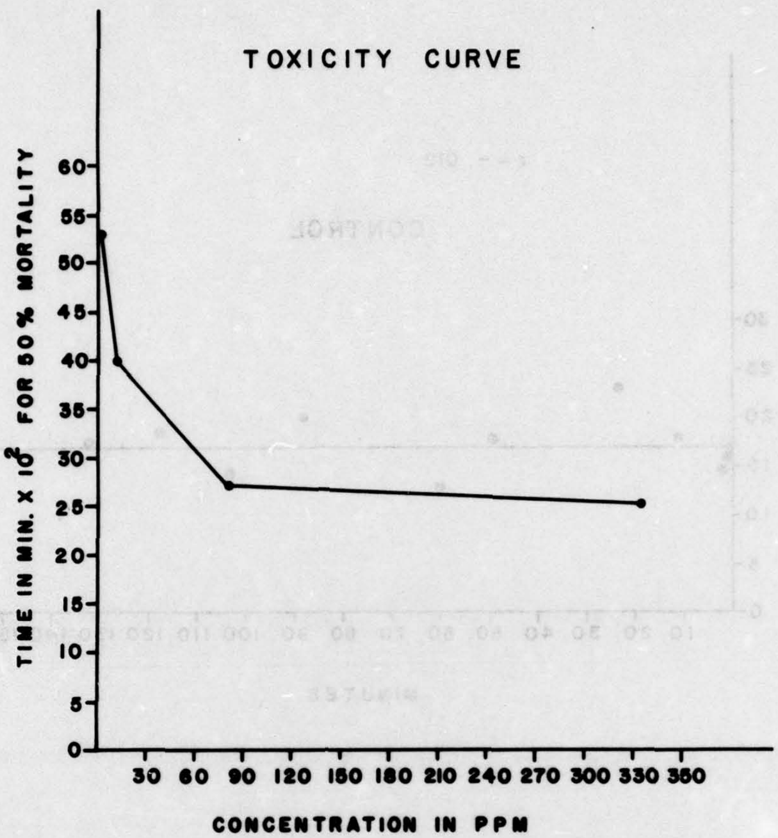


Figure 4. Oil Uptake



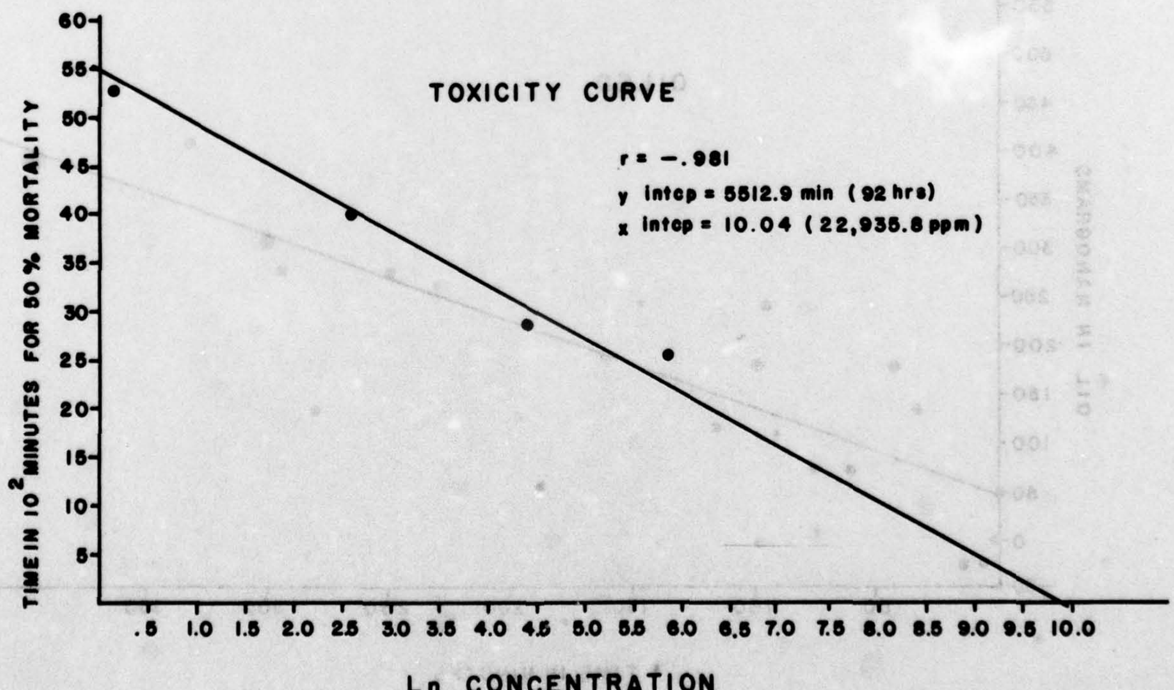
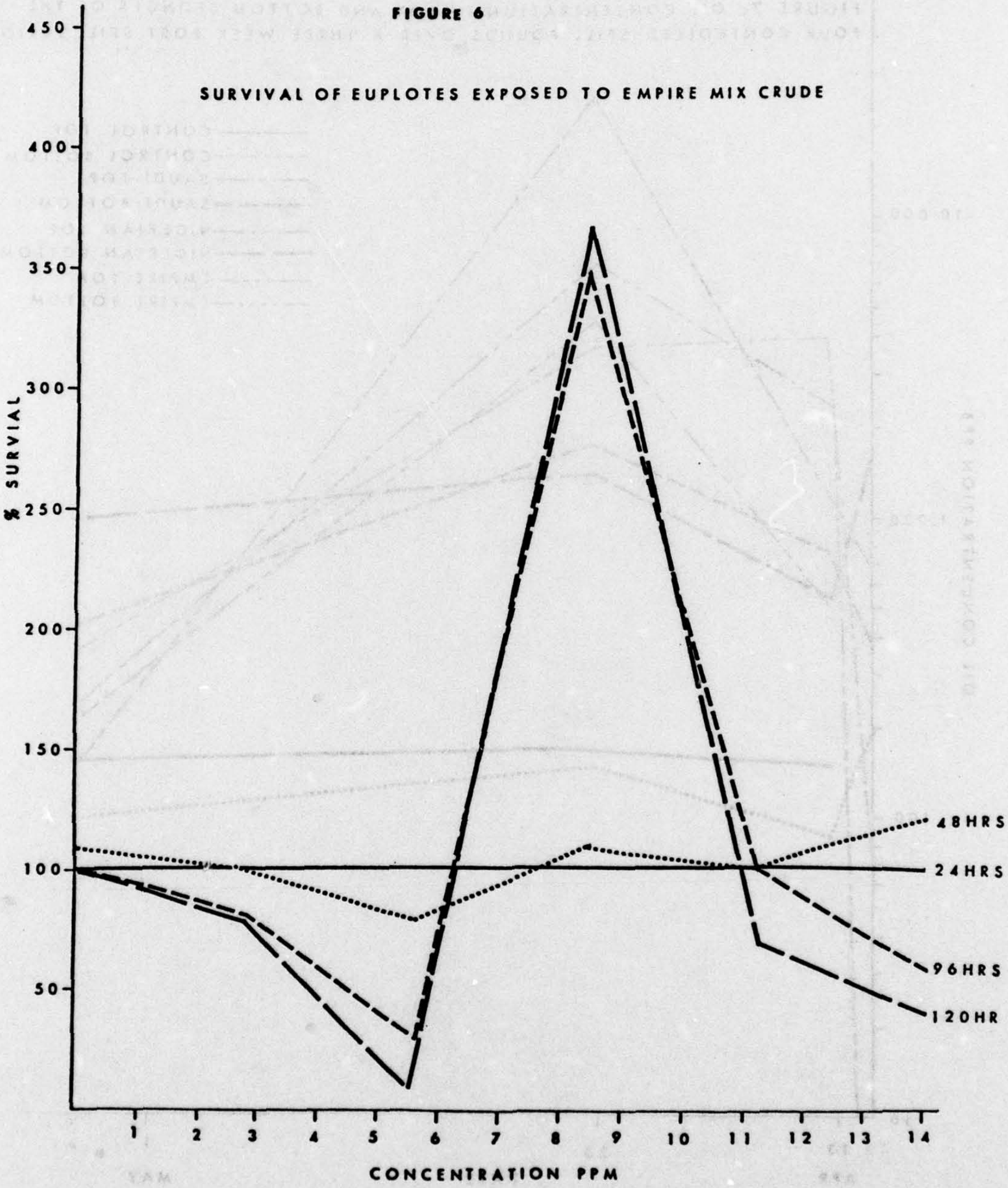


Figure 5. Toxicity Curves

FIGURE 6

SURVIVAL OF EUPLOTES EXPOSED TO EMPIRE MIX CRUDE



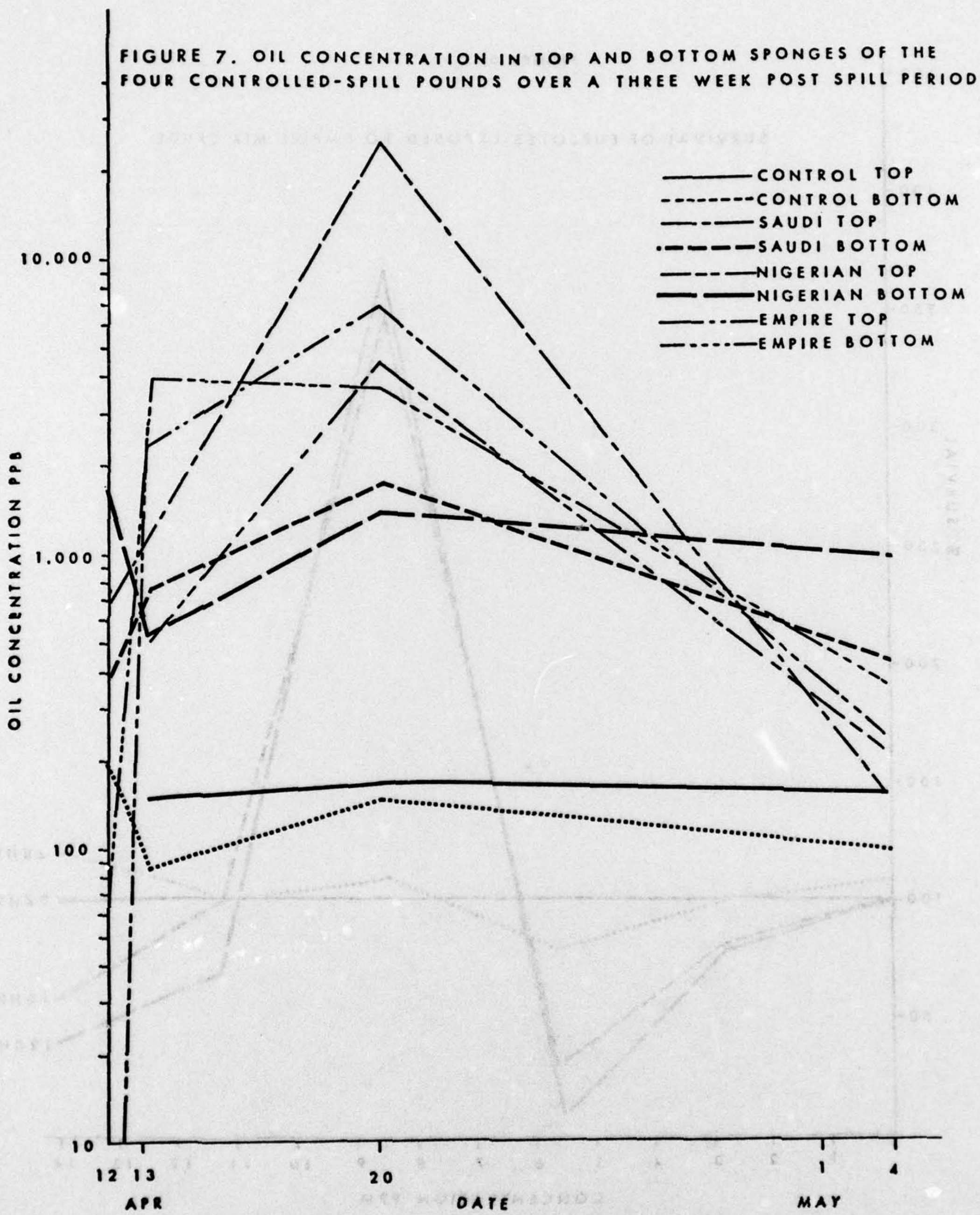


FIGURE 7. OIL CONCENTRATION IN TOP AND BOTTOM SPONGES OF THE FOUR CONTROLLED-SPILL POUNDS OVER A THREE WEEK POST SPILL PERIOD
CONTROL TOP
CONTROL BOTTOM
SAUDI TOP
SAUDI BOTTOM
NIGERIAN TOP
NIGERIAN BOTTOM
EMPIRE TOP
EMPIRE BOTTOM
OIL CONCENTRATION PPB
10,000
1,000
100
10
12 13
APR
20
DATE
1
4
MAY

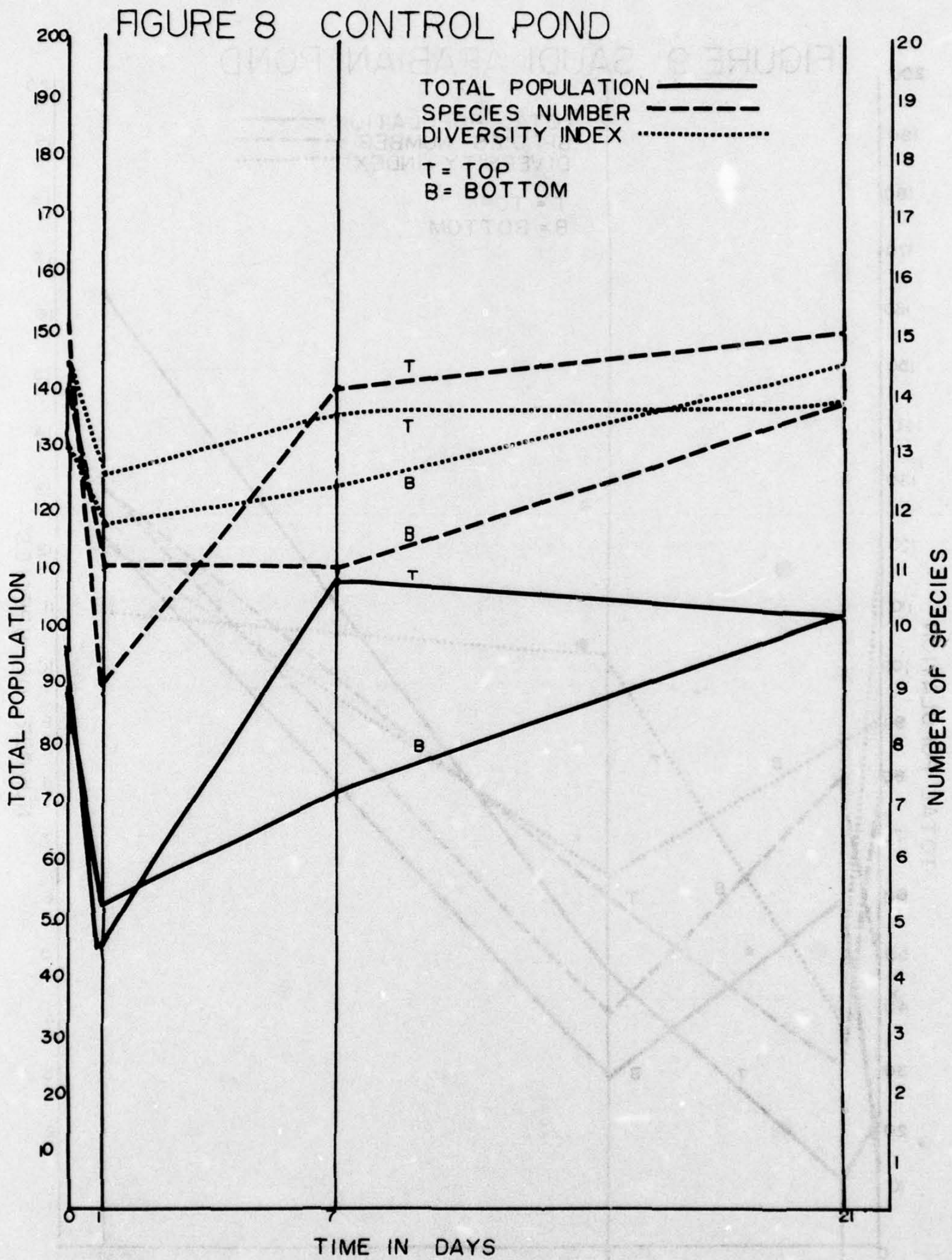


FIGURE 8 CONTROL POND
TOTAL POPULATION
SPECIES NUMBER
DIVERSITY INDEX
T = TOP
B = BOTTOM
T
T
B
B
T
B
TOTAL POPULATION
NUMBER OF SPECIES
TIME IN DAYS
0
1
7
21
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

FIGURE 9 SAUDI ARABIAN POND

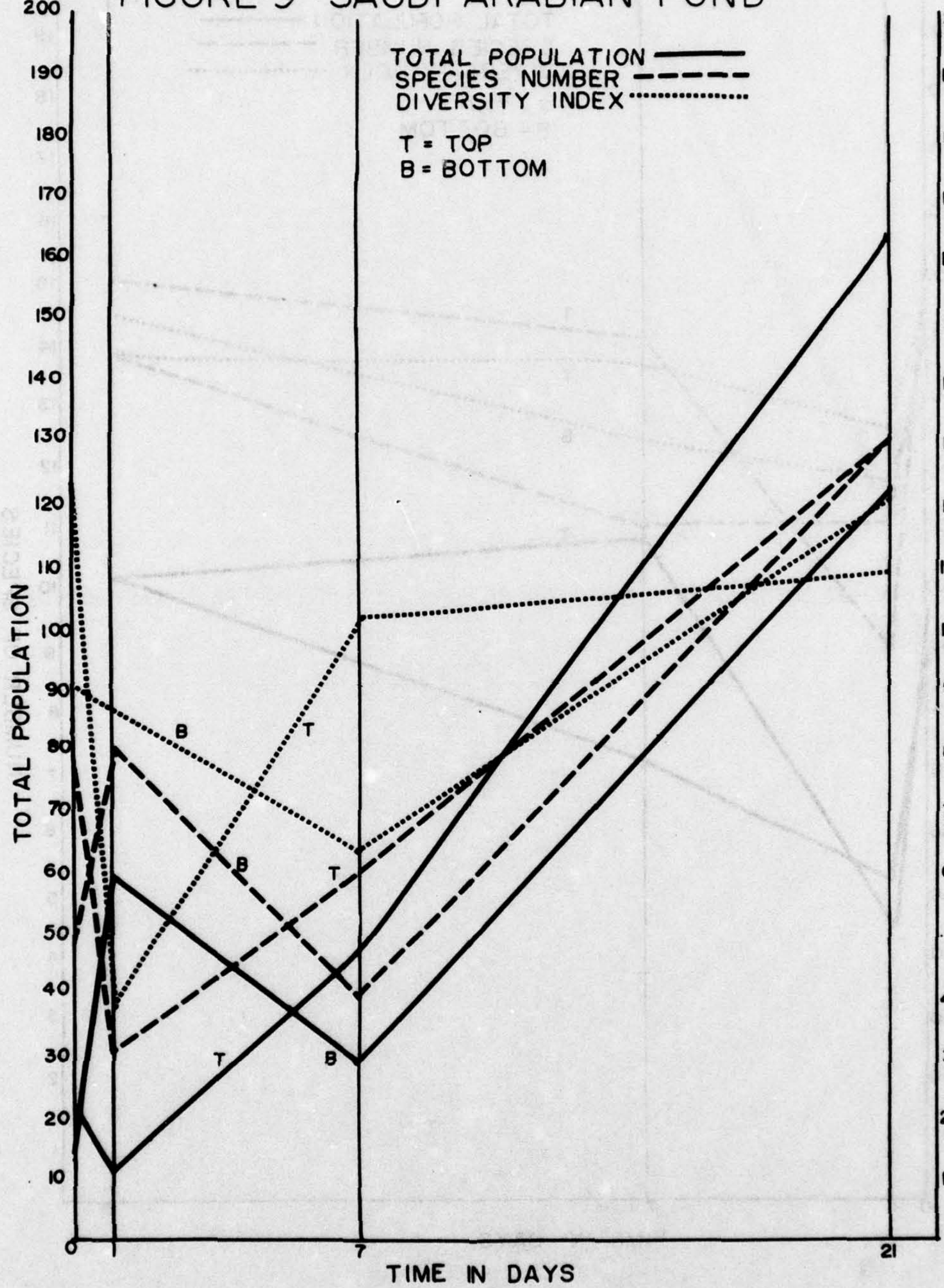


FIGURE 10 NIGERIAN POND

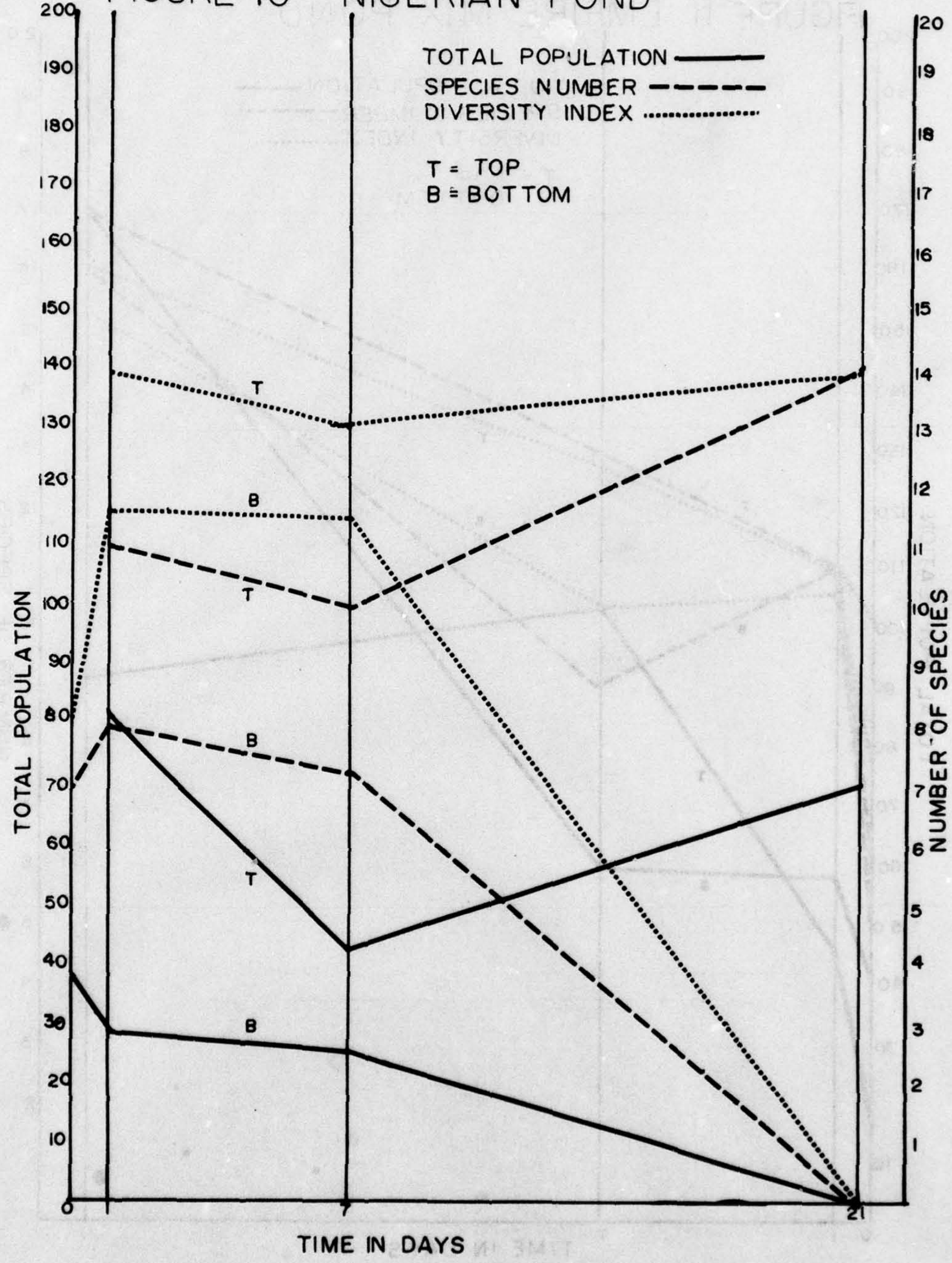
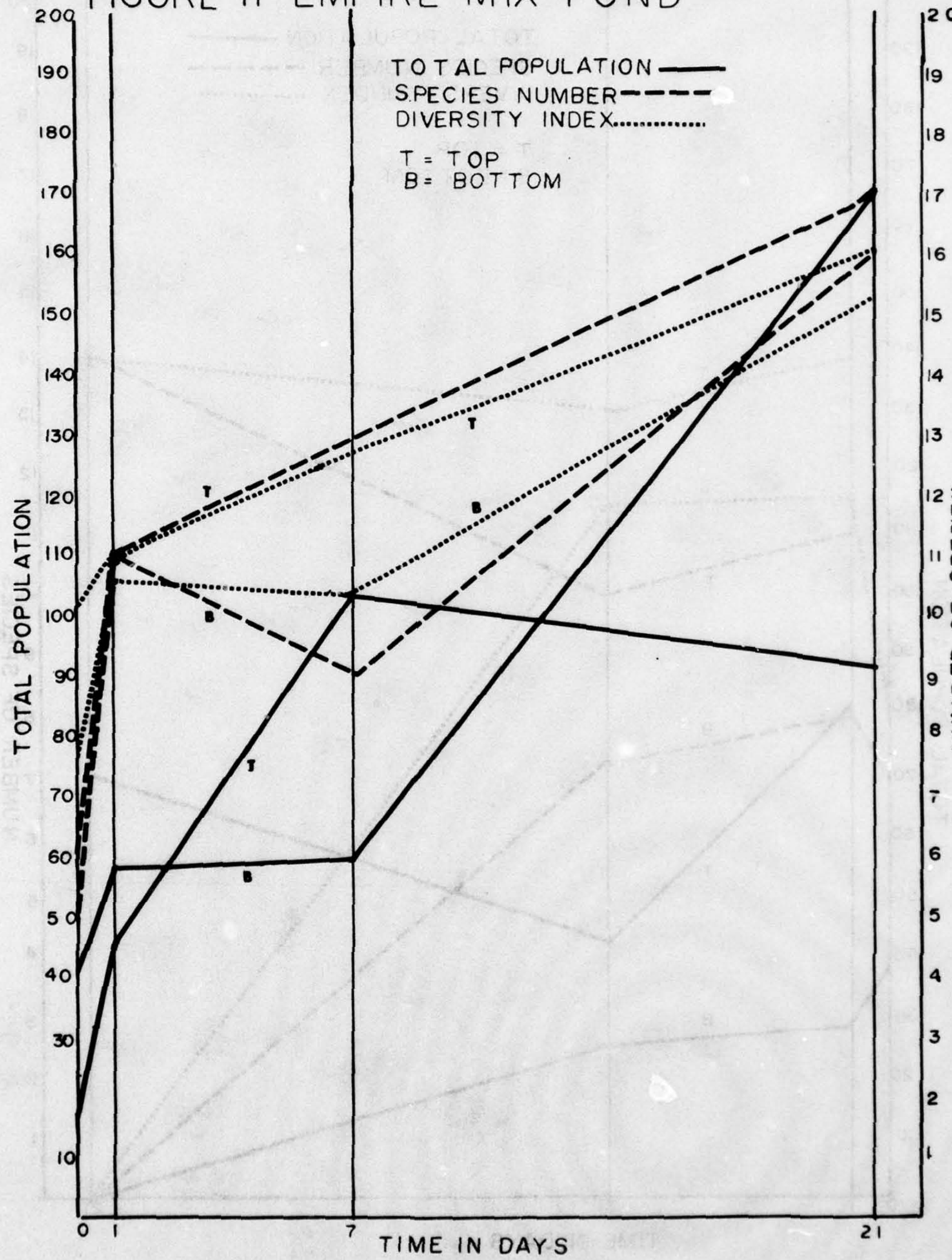


FIGURE II EMPIRE MIX POND



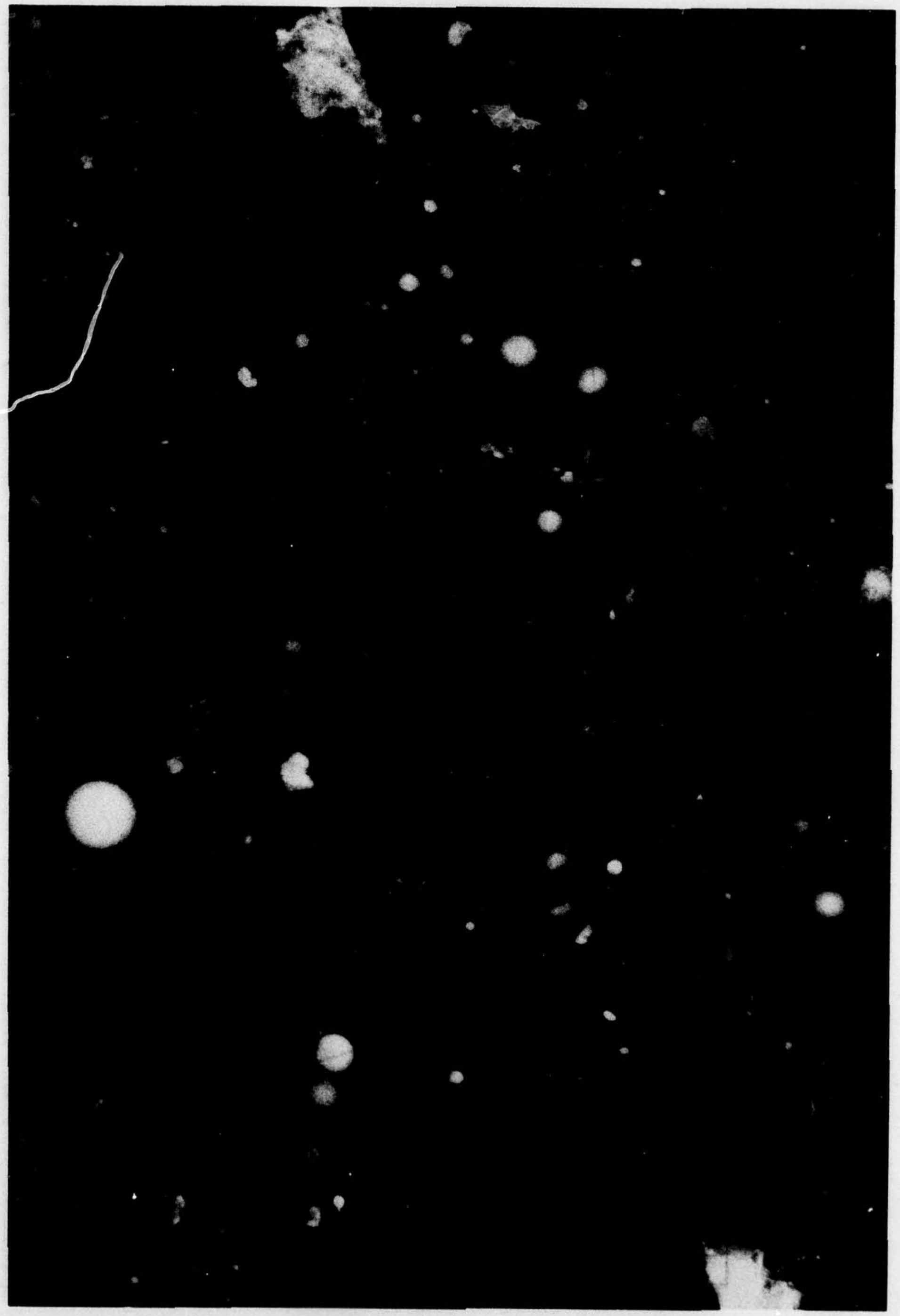
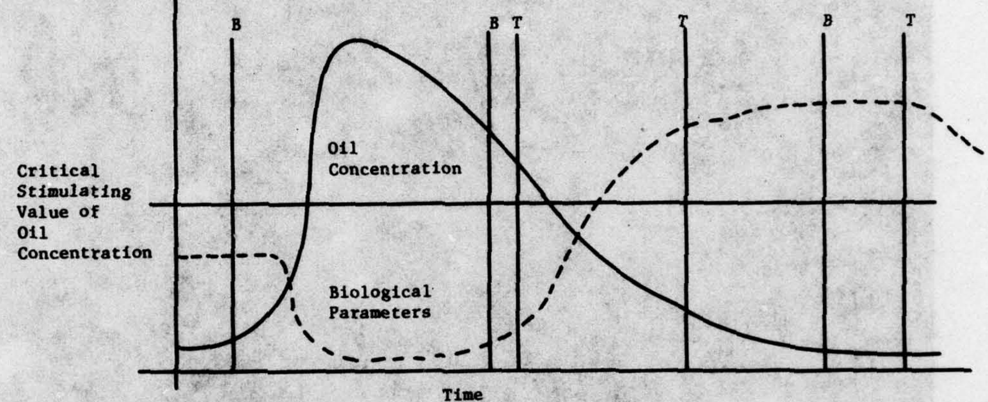
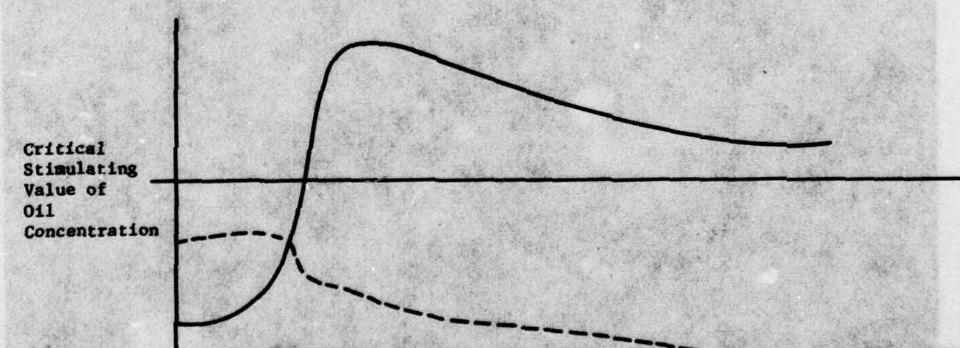


Figure 12. Fluorescence photomicrograph of detritus in Saudi Arabian oiled pond seven days after oiling. Note particles coated with fluorescing oil and droplets of oil embedded in detritus. 100X.

FIGURE 13. Theoretical Relationship of Oil Concentration and Biological Parameters Over Time



(a) Postulated relationship between oil concentration and biological parameters (population, species number) for substrates in the Empire Mix at Saudi Arabian crude oiled ponds. B-lines represent postulated sampling times for bottom substrates; T-lines represent sampling times for top substrates.



(b) Postulated relationship between oil concentration and biological parameters in bottom substrate of Nigerian crude oiled pond.

EFFECTS OF LOW LEVELS OF HYDROCARBONS ON EMBRYONIC, LARVAL AND ADULT WINTER FLOUNDER, (*Pseudopleuronectes americanus*)[1]

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3. Environmental Research Laboratory, EPA, Narragansett, R.I., USA
4. Biology Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543 USA
5. Marine Pathology Laboratory, University of Rhode Island, Kingston, R.I., USA

1. Address inquiries to J. J. Stegeman, W. W. Kühnhold or D. Everich

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ABSTRACT

Direct exposure of winter flounder eggs to 100 ppb water-accommodated No. 2 fuel oil resulted in reduced viable hatch when the exposure duration included both *fertilization* and embryonic development. Hatching was delayed when exposure included contamination of gametes during gonad maturation, and spinal abnormalities appeared in these fish also. Progeny resulting from gametes contaminated solely during gonad maturation by exposure of adults to 10 or 100 ppb oil showed reduced larval survival and growth. Other developmental events from fertilization through hatching were not influenced by this exposure and progressed normally. The adult females exposed during gonad development possessed fuel oil hydrocarbons in their tissues, yet did not show any exposure-related changes in hepatic cytochrome P-450, benzo[a]pyrene hydroxylase or aminopyrine demethylase. Similarly, hepatic lipogenesis and TCA cycle activity were not affected by this exposure, nor was hepatic histology. Thus, latent affects on reproductive success can occur even though earlier developmental stages or adults appear unaffected.

1 Address inquiries to J. J. Stegeman, W. W. Kühnhold or D. Everich

INTRODUCTION

The modes by which foreign compounds introduced into the aquatic environment may possibly influence reproductive success in fishes are varied. 1) There may be immediate or delayed effects on gametes, or on embryonic or larval stages, following direct exposure some time after release of gametes by the adult. 2) Effects on progeny may result from contaminants incorporated into gametes, via the adult, during some stage of gametogenesis or gamete maturation. 3) Foreign compounds may adversely affect adult physiology and interfere with normal gametogenesis, influencing the number or quality of gametes. 4) There could be effects on ecological factors such as availability of appropriate substrate for spawning, larval food supply, or predator abundance, etc., related to successful spawning or development.

Previous studies have demonstrated that direct exposure of fish eggs and larvae to high concentrations (1-10 ppm range) or petroleum hydrocarbons will elicit toxic effects including mortality (Mironov, 1967, 1969; Kuhnhold, 1969, 1974; Struhsaker et al., 1974; Eldridge et al., 1977; Johannessen, 1977). There have, however, been few studies concerning the effects of low levels (10-100 ppb range) of hydrocarbons on reproduction or development in fishes, and there is little information concerning the influence of contamination by routes other than direct exposure of eggs or larvae on reproductive success.

The present study was undertaken to assess low level exposure effects on reproduction in winter flounder. The toxicant selected was #2 fuel oil, a petroleum product commonly introduced into coastal waters (Hyland, 1977). The parameters examined in eggs and larvae were related to fertilization, viability and developmental patterns. At the same time adult animals were examined for histological and biochemical changes in hepatic tissue and hydrocarbon content of gonadal, hepatic and muscle tissue. The results are discussed in the context of their implications for success of fish reproduction in oiled environments. They are also considered in terms of the significance of effects appearing in adult as contrasted to embryonic and larval fish.

MATERIALS AND METHODS

Winter flounder (*Pseudopleuronectes americanus* Walbaum) were obtained in outer Narragansett Bay, Rhode Island, by otter trawl, in November 1976 through February 1977, and experiments initiated from December 1976 to March 1977. The animals varied in size between 24.0 and 34.5 cm for males, and 27.5 and 40.0 cm for females. All animals were sexually mature, and were in various stages of gametogenesis at the time of capture. Salinity averaged 31.4‰, and temperature ranged from 1° to 10°C over the exposure periods of mid-December to mid-April, which during most of the experimental period was somewhat colder than normal. Temperature in Narragansett Bay averaged 2.6°C during the experimental period, 1.5°C lower than the average temp-

erature for the same period during the previous year. Winter flounder normally do not feed at extremely cold temperatures nor during most of gametogenesis and spawning, hence neither control nor experimental adults were regularly fed. Food occasionally offered was rejected.

The fuel oil used in these experiments was obtained from Exxon Oil Co. and had an aromatic content of 33%. The experimental dosing apparatus at EPA-ERL, Narragansett, R.I., was used for exposure of adult animals, and Figure 1 shows a schematic of this apparatus. The flow of the primary water-accommodated petroleum fraction and the amount of additional clean seawater were adjusted in a way to obtain nominal dose levels of 10 and 100 ppb total CCl_4-extractable hydrocarbons, measured by infrared spectrometry. This system has been used and described previously (Hyland *et al.*, 1977). The adult animals were exposed to actual dose levels averaging 12 ppb for 3 days to 8 weeks, and to 90 ppb for 4 to 11 weeks. Control fish were maintained in similar tanks without the addition of oil. Gametes from control and experimental animals both male and female, exposed for varying periods, were stripped and fertilized *in vitro* as required, for the various studies on fertilization and hatching, or larval growth and survival. The adults were used for physiological studies as well. A schematic course of the study is shown in Fig. 2.

Embryonic and Larval Studies

Fertilization and Hatching: To facilitate microscopic monitoring of the embryos, newly spawned eggs were allowed to adhere to microscope slides which were then positioned in 250 ml beakers. Each slide could be easily removed and examined with a minimum of egg handling. An appropriate number of microscope slides were placed in the bottom of a glass finger bowl containing 100 ml of clean or oil contaminated sea water. A small amount of eggs (approximately 1 ml) were stripped from the female into the dish. Milt from two males was added, and the bowl was swirled to thoroughly mix the gametes and spread the eggs evenly over the slides. After 30 min the eggs were rinsed and percent fertilization, indicated by appearance of the perivitelline space, was measured. Excess eggs were removed from the slide until 100 well-separated fertilized eggs remained, and the slide was placed in an exposure beaker and supplied with flowing clean sea water, or water from the dosing system. Salinity averaged 31‰ and temperature ranged from 3°-12°. Dose levels averaged 11 ppb and 104 ppb. Every 48 hrs the eggs were examined for mortality and abnormalities. When the first larvae began to hatch, the eggs were examined every 24 hours for embryonic mortality, total hatch and 24 hr viable hatch.

Larval Growth and Survival: Hatching takes place over a 4-5 day period, however a major part of the eggs hatch on one day. On this day at least 10 larvae were sacrificed and measured (notocord

length). Four days later all surviving larvae were sacrificed and counted and a representative sample measured to determine early larval growth and survival. As the temperature and consequently rate of larval development increased seasonally, the time interval for measurement of growth was changed to 3 days to insure that growth was measured at the same developmental stage through-out the experiment. Data were analyzed statistically using paired Student's Tests or analysis of variance followed by least significant difference analyses to compare specific means (Snedecor and Cochran, 1967). Due to inadvertently reduced water flow to beakers holding 10 ppb exposed eggs, data and conclusions from these groups are quite limited.

For extended larval growth and survival studies larger numbers of larvae were used. Body weights and lengths, exposure times and mean concentrations for the females from which eggs were taken for these particular studies are summarized in Table 1. Eggs of exposed or control adults were stripped and fertilized after the method described by Smiegielski (1975) from animals not treated with pituitary extract. The eggs were incubated in nitex screen baskets suspended in 30 ℓ aquaria. To inhibit bacterial growth the water was initially treated with 25 ppm streptomycin and 25 ppm penicillin.

The water was well aerated but not changed. After hatching of the major part of the larvae they were transferred to a second aquarium and held for 4 days to obtain viable larvae for further rearing. Then 500 normally active individuals were transferred into a third aquarium and fed with natural plankton. Procedures for handling of food and feeding were those described by Laurence (1977) and, during the rearing period a food concentration of 1 to 2 plankters per ml was maintained. Plankton was added daily, and water renewal was only achieved with the addition of plankton.

<u>O_2-Consumption</u>: Oxygen consumption rates were determined only for eggs and larvae derived from adults exposed during gonad maturation. Generally, six samples of 50 or 100 eggs were taken twice weekly, and 15 larvae were taken from the feeding tanks once a week, except in those cases showing a constant decrease in the total number of larvae. O_2 consumption was measured over 2 hrs, sometimes extended when the readings were very low. Standard length of the larvae was measured immediately after the respirometer procedure, dry weight (90°C, 1 day) after fixation in 1% formaldehyde.

Hepatic Function in Adults

Studies on adult fish were conducted using females, both control and variously exposed, including those that were the source of eggs used in studies of fertilization, hatching and larval development. Sizes of females used in this work were 504 ± 185 g, 434 ± 134 g and 510 ± 106 g for control, 10 ppb and 100 ppb respectively. Fish were sacrificed generally within 48 hrs after eggs had been stripped. Livers were removed *in toto* and portions were placed immediately in

ice cold Krebs Ringer bicarbonate buffer for metabolic studies, or in 10% buffered formalin for histological assessment. The remainder was wrapped in solvent-cleaned foil and frozen for eventual hydrocarbon analysis.

Acetate Metabolism: Approximately 150 mg portions of each liver were minced and incubated at 20°C with acetate-1-^{14}C as previously described (Sabo and Stegeman, 1977). Incubations were stopped with 2N H_2SO_4 and CO_2 generated was trapped with 1 N NaOH. Tissue lipids were extracted according to Dole (1956) and partitioned into hexane. Aliquots were evaporated under nitrogen to remove any volatile lipids then redissolved in hexane. ^{14}C incorporated into CO_2 respired or lipids synthesized was determined by scintillation counting. Analyses were performed in triplicate and blanks consisted of acetate-1-^{14}C incubated without tissue, but otherwise treated as samples.

Mixed-Function Oxygenases: Liver tissue was homogenized at 5 volumes/g in 0.065mM phosphate buffer pH 7.0, containing 3 μM $MgCl_2$ and 1.15% KCl, using a Potter-Elvejhem tissue grinder. Microsomal fractions were prepared from 10,000 x g supernatants by centrifugation at 40,000 x g for 1.4 hrs. Microsomal pellets were resuspended in 0.1 M phosphate, pH 7.3 at a concentration of 7-9 mg protein/ml. Benzo[a]pyrene hydroxylase and aminopyrine demethylase were assayed as previously described (Stegeman, 1978) at a pH of 7.1 and temperature of 29°, using modifications of the procedures of Nebert and Gelboin (1968) and Cochin and Axelrod (1959). Blanks consisted of reactions carried out without an NADPH generating system.

Microsomes were diluted to 0.6-1.0 mg protein/ml in 0.1 M phosphate buffer, pH 7.3, and cytochrome P-450 analyzed optically in CO-bound, $Na_2S_2O_4$ reduced samples versus CO-bound reference, with a Cary 118-C recording spectrophotometer. Cytochrome content was estimated using an $OD_{450-490}$ extinction coefficient of 91 $mM^{-1}cm^{-1}$ (Omura and Sato, 1964). Protein was determined according to Lowry *et al.* (1951) using bovine serum albumin as a standard.

All assays were performed at least in duplicate on individual animals and data were analyzed using standard t tests performed on variance estimates (Sokal and Rolf, 1969). The results considered here are only those for female fish as experimental males sampled were too few for data to be grouped in any way that was amenable to statistical treatment.

Histopathology: Liver tissue was fixed immediately after sacrifice in 10% formalin. Tissue was imbedded in paraffin, sectioned at 6 microns and stained using Mayer's hematoxylin and aqueous eosin stains.

Hydrocarbon Analysis

Samples of tissue from exposed and control fish were placed in 150

ml glass centrifuge bottles with Teflon lined caps and subsequently prepared for analysis immediately, or frozen for later preparation. The procedure used for analysis of hydrocarbon content of tissue samples was similar to one described elsewhere (MacLeod, *et al.*, 1976). Tissues were digested with 4N NaOH (in capped centrifuge tubes) overnight at 37°C. The samples were then extracted three times by shaking with 50 mls of CH_2Cl_2 each time. Emulsions were broken by centrifugation at 12,500 rpm in stainless steel centrifuge bottles. The CH_2Cl_2 extracts were combined and passed through a chromatographic column of silica gel and Na_2SO_4. The extract was reduced in volume on a Kuderna-Danish evaporator, solvent exchanged to hexane, and charged onto a silica gel column. The sample was eluted with pentane (aliphatic fraction) and 20% CH_2Cl_2 in pentane v/v (aromatic fraction). These fractions were reduced in volume under a stream of nitrogen, solvent exchanged to hexane and an aliquot was analyzed by gas chromatography (GC) and gas chromatography - mass spectrometry (BC-MS). For water analysis six liters of water obtained from the 100 ppb tank of the dosing system were extracted three times with 100 ml of CH_2Cl_2 in a separatory funnel. The combined extracts were passed through a column of Na_2SO_4, reduced in volume on a Kuderma-Danish evaporator, and solvent exchanged to hexane. Aliquots of the extracts were then analyzed by gas chromatography.

GC analyses were performed on a 30 meter glass capillary column (SE-52) in a Hewlett Packard 5840-A gas chromatograph. The G.C.-M.S. analysis used a similar column in a Shimazdu Model GC-4CM G.C. connected to a Finnegan 1015 mass spectrometer equipped with a Systems Industries data system. Reagent blanks were periodically processed to ensure continued satisfactory performance of the methods. Estimations of the quantities of No. 2 fuel oil in tissues were made based on comparisons of areas, determined by planimetry, from sample chromatograms with areas from external standards of No. 2 fuel oil.

RESULTS

Hydrocarbon Accumulation in Tissues: Figure 3 shows a chromatogram of the whole No. 2 fuel oil, and a chromatogram of whole extracts of water from the dosing system. The whole oil showed regularly spaced n-alkane peaks ranging from n-C_8 to n-C_{23}. Between these peaks other peaks from aliphatic, naphthenoaromatic, and aromatic compounds were evident. Comparison of this chromatogram with that of the water in the 100 ppb tank showed relatively larger aromatic peaks (methylnaphthalene, C_2-naphthalenes, and C_3-naphthalenes) present in the chromatogram from the dosing water. This enrichment of aromatics relative to aliphatics in the water of the dosing system is believed to partly reflect the greater water solubility of the lower molecular weight aromatics.

A chromatogram of the aliphatic fraction obtained from the No. 2 fuel oil, and the aliphatic fraction from a flounder liver (female No. 300; 100 ppb exposure for 80 days) are shown in Figure 4. The gas

chromatogram from this tissue sample showed compounds in the range of n-C_9 to n-C_{12}, and an area with very few peaks from n-C_{12} to n-C_{19}. Above n-C_{19} natural fish oils were evident as the large hump observed in aliphatic fractions obtained from all other samples of flounder tissues. Further analyses revealed identical mass spectra for many peaks in the oil and in the liver extracts.

The gas chromatograms of aromatic hydrocarbons obtained from tissues of flounder exposed to 10 ppb and 100 ppb oil were similar to each other, and clearly resembled chromatograms of aromatics from the No. 2 fuel oil used in the dosing experiments. The chromatographic similarity of aromatics from the dosing oil and flounder liver (female No. 300) are illustrated in Figure 5. The aromatics tentatively identified by GC-MS in the oil and in the flounder liver extracts are listed in Table 2. These data and the similarity of chromatograms in brackets 6 (mostly C_1-napthalenes), brackets 7 (mostly C_2-naphthalenes), and brackets 8 (mostly C_3-naphthalenes) indicate that aromatics from the No. 2 fuel oil were present in the tissues.

Concentrations of hydrocarbons in hepatic tissue of several groups of fish are given in Table 3. There were no detectable fuel oil hydrocarbons in control fish. Levels of aliphatics were lower in all samples than were levels of aromatics, for fish exposed either to 10 or 100 ppb fuel oil. The concentrations of aromatics were no greater in liver of fish exposed for 75 days to 100 ppb, than in fish exposed for 33 days. While fuel oil hydrocarbons did appear in the other tissues examined including ovary, the data have not yet been quantified.

Fertilization, Embryogenesis and Hatching: The impact of direct exposure of eggs to the water-accommodated fraction of #2 fuel oil was expressed as the reduction in the 24 hr viable hatch. These values for several exposures are compared in Figure 6. Statistical analysis revealed no difference in the hatching success after exposure to 10 ppb during any combination of developmental stages. However, the exposure to 100 ppb throughout gonad maturation, fertilization, and incubation resulted in a 19% reduction in viable hatch compared to control fish, a difference which was highly significant ($P < 0.025$). The difference in hatch between control eggs and those exposed to 100 ppb during fertilization and incubation was also about 19%, significant at $P < 0.05$, suggesting that exposure during these two stages may have accounted for the effect seen in the previous case as well. On the other hand, oil exposure exclusively during either incubation or gamete maturation was associated with reduction in viable hatch which only approached significance ($0.05 < P < 0.10$). These results suggest that relatively more damage, expressed as viable hatch, was incurred when exposure included fertilization and incubation, but the impact was not due solely to exposure during the latter.

Several effects less dramatic than mortality but with possible ecological consequence were observed. Hatching was delayed by 3-9 days ($\bar{X}$=7) for eggs exposed to 100 ppb of oil throughout gamete

maturation, fertilization, and incubation. In addition, a 4% incidence of spinal abnormality occurred in larvae from this group while none occurred in controls. A less marked hatching period extension averaging 2 days (0-6 days) was exhibited by eggs exposed to 100 ppb of oil during incubation only, and during fertilization and incubation.

Statistical analysis similar to that used for viable hatch data revealed no significant differences in percent fertilization or total hatch, within any exposure regime.

Larval Growth and Survival: As indicated above, the impact of 10 ppb oil did not influence the 24 hr viable hatch of eggs undergoing any combination of exposures. The impact of 100 ppb on viable hatch was significant, but not when exposure was solely through gametogenesis, or gamete maturation. Larvae produced from gametes contaminated during gamete maturation were therefore examined for hidden or delayed sublethal defects.

The results of larval growth and survival are presented in Figures 7 and 8. At feeding conditions between 1 and 2 plankters/ml the mortality coefficient for winter flounder larvae ranges from 0.036 - 0.059 (Laurence, 1977), indicated by the shaded area in Figure 7. A range is given here as the food concentration was not adjusted to an exact number but varied within these limits, and occasionally may have been even higher than 2 plankters/ml. Using Laurence's figures the vertical black bars indicate the expected range of remaining larvae, taking into account the reduction of the total number due to periodic taking of samples for dry weight determination. Each symbol below one of these bars thus represents the actual number found to survive until the time the aquaria were emptied. The mortality coefficient calculated for the control animals fell within the range of expected values, with $b_{con} = 0.045$. Plots for larvae from both the 10 ppb and 100 ppb exposured females were so similar on visual inspection that the data were pooled to calculate a regression curve, and the resulting mortality coefficient, $b_{ex} = 0.130$, was very much higher than that expected for untreated animals, between 0.036 and 0.059.

The growth curves, shown as semilog-regression lines for larvae of each female of the 100 ppb-group, also indicate a lower growth coefficient for treated animals. The range of the growth coefficients of the experimental groups was 0.220 to 0.284 and the control was 0.334.

O_2 Consumption: It was thought that O_2-consumption might reflect physiological condition of eggs and larvae contaminated through parental exposure. The best fit for the regression lines (Fig. 9) was achieved by the exponential equation $y = a\,c^{bx}$, where y is O_2 consumption expressed as µl per hour per organism and x is time in days. Comparison of the curves themselves and the exponential co-

efficients "b" reveals no consistent difference between the eggs from contaminated females and the control. In all cases except for one, female No. 109, the initial oxygen consumption was slightly higher than in the control. Yet the total consumption decreased in all cases, eventually becoming lower than the control as expressed by coefficient "b", again except for No. 109 which exceeded the control after hatching.

As described above the average growth of the parentally contaminated larvae differed from the average normal growth. This result suggested that a calculation of the specific oxygen consumption, dependent on the dry weight of the larvae, be made. The specific oxygen consumption of the larvae from 100 ppb-exposed females was then plotted against body dry weight and the regression coefficients compared (Fig. 10). This oxygen consumption was quite parallel with growth. The growth coefficients decreased with the same sequence of maternal source (109, 108, 112, 306) as did the coefficients for the specific oxygen consumption (Fig. 10). Values of the initial oxygen consumption, given by the intercept, are not relevant as the description of the regression by $y = ac^{-bx}$ is the best fit only for the plots with $x > o$, and is not valid for $x = 0$ or even x closed to zero.

Adult Physiology: The animals used in all of these studies were allowed to mature and hydrate naturally and thus spawning, hence sampling, occurred very irregularly. As a consequence, samples of adults at any given time, whatever the exposure conditions, were comprised of very few animals. Most of the results, however, could be grouped either within seasonal periods of sampling, or according to length of exposure. Results of both groupings are presented, as they serve to distinguish seasonal from exposure-related effects.

All of the fish sampled could be grouped according to sampling time. In the latter case one set of control and exposed fish consisted of animals sampled between January 1 and February 2, and included exposures to petroleum for 14 to 50 days. The second set included animals sampled between February 17 and March 18, with exposures of from 10 to 63 days. These groups, exposed both to 10 and 100 ppb, included those few animals which were used for hydrocarbon analysis and those used as a source of gametes for studies with embryos and larvae.

Characteristics of the liver and rates of hepatic lipogenesis and CO_2 production for the animals grouped according to date are given in Table 4. It is apparent that for fish sampled in January there were no significant differences in any of these parameters between control animals and those exposed to either 10 or 100 ppb. There was also no difference between animals exposed to 10 ppb sampled during February-March and their controls. There was, however, a trend toward lower rates of incorporation of ^{14}C into $^{14}CO_2$ in both the control and experimental groups sampled in February-March than

in those animals sampled in January.

Table 2 gives some characteristics of microsomal mixed-function oxygenases in these same groups. As with the previous aspects of hepatic function, there were no significant differences in the rates of benzo(a)-pyrene hydroxylase or aminopyrine demethylase, nor in the optical properties or content of cytochrome P-450 or the content of microsomal protein, between any of the exposed or control groups sampled in January. Similarly, there were no differences between control and exposed fish sampled in February-March. Again, a difference was apparent between animals, whether control or experimental, sampled in February-March and those sampled in January, but only in benzo(a)pyrene hydroxylase activity. In this case the trend was toward greater activity in the February-March samples.

While the above data suggest that the exposures here did not elicit any changes in hepatic function, it is possible that effects of exposure might be masked in these groups of varied exposure duration. In several cases the variance was quite high, which could permit the interpretation that animals in a given group may be showing both increased and decreased rates of function in response to exposure, possibly related to duration of exposure, even though the hydrocarbon analyses suggested no great differences in content of hydrocarbons.

Data from only a portion of the animals exposed to a given concentration and their pair-sampled controls could, however, be grouped in sufficiently large groups according to length of exposure. These were animals exposed to 10 or 100 ppb for 14-15 days, and to 10 ppb for 50-57 days.

The results for groups formed according to length of exposure are presented in Table 3. At 14-15 days exposure, there appeared to be a trend toward increased ^{14}C-lipogenesis and $^{14}CO_2$ production in the fish exposed to 10 ppb, yet this was not apparent either in the fish exposed to 100 ppb for the same period, or in fish exposed to 10 ppb for 50-57 days. While transitory phenomena are possible, it seems unlikely that they would occur at this extremely low concentration, when 100 ppb exposure for the same period did not elicit an apparent change. The activity of benzo(a)pyrene hydroxylase was not different between any exposed fish and pair-sampled controls, whether expressed on the basis of mg microsomal protein, or nanomoles cytochrome P-450 (an estimate of turnover number).

While revealing little effect of exposure, the data in Table 3 do, however, express large differences between control or experimental animals sampled at 14-15 days and those sampled at 50-57 days. The former were all sampled in mid-January, and the latter in late February. These differences confirm the seasonal trends, suggested in Tables 1 and 2, to increased benzo(a)pyrene hydroxylase and decreased $^{14}CO_2$ generation in animals sampled in February or March. In the case of benzo(a)pyrene hydroxylase the differences in apparent turnover number, i.e., activity per nanomole of cytochrome P-450, between these

sampling periods were particularly striking.

Histopathology: Livers examined histologically included most of those used for studies of hepatic function, and those used for hydrocarbon analysis and as a source of gametes. None of the livers of 34 fish examined showed significant lesions in any exposed or control group. No significant differences in cellular appearance between the groups were noted, exemplified by photos of a typical histological preparation shown in Fig. 11. There was some fatty change in the livers yet the degree of fatty metamorphosis varied from fish to fish. This condition was not significantly more prevalent in any experimental or control group and appeared within normal ranges in all these groups.

DISCUSSION

The results presented here describe subtle effects of very low levels of petroleum on winter flounder reproduction and larval physiology. These effects varied with level and mode of exposure, while at the same time enzymatic, metabolic and histological parameters in the liver of adults undergoing the same exposure appeared unchanged.

Previous work investigating the influence of petroleum hydrocarbons on fish reproduction and development has dealt primarily with direct exposure of embryos and in some cases larvae (Anderson et al., 1977; Kuhnhold, 1972, 1974, and 1977; Linden, 1976; Rice et al., 1975). Information concerning the more critical or more sensitive stages of embryonic and larval development resulted from some of these studies (Kuhnhold, 1972, 1974, and 1977; Rice et al., 1975). The general conclusions are: (1) during embryogenesis, sensitivity decreases with age; (2) during larval development, sensitivity increases with age; (3) larvae are more sensitive than embryos. In the present investigation we examined effects on fish reproduction in a broader way. Exposure parentally during gametogenesis or gamete maturation and at fertilization as well as during embryogenesis was carried out, and a suite of parameters were measured to detect both immediate and delayed responses.

A significant reduction in viable hatch was observed only for those exposures which included both fertilization and embryogenesis. Since exposure during fertilization exclusively was not tested, we could not discern whether the reduction resulted from effects during fertilization, embryogenesis, or both. It seems probable, however, that the observed response was the result of a combination of effects during both fertilization and embryogenesis. While there are no reports of deleterious effects of oil on fertilization the possible entry of water into the perivitelline space could provide for rapid petroleum hydrocarbon incorporation into the egg and subsequent effect. It is also possible that aspects of sperm capacity may be affected yet this seems unlikely since no reduction in percent fertilization was observed.

The trend to reduction in viable hatch following exposure solely during embryogenesis, while not significant, does suggest that some damage was incurred at that stage. Work mentioned previously has demonstrated effects due to embryonic exposure. In addition Anderson et al. (1977) have shown that the chorion is not a barrier to petroleum hydrocarbons and uptake of these compounds from the water during embryogenesis does occur.

An effect on viable hatch, rather than total hatch, has also been observed by other investigators (Ernst et al., 1977; Kuhnhold, 1972 and 1974; Linden, 1976; Struhsaker et al., 1974). A high incidence larval abnormalities usually accompanied such effects. We found only a low incidence of obvious abnormalities, possible a feature of very low treatment levels, but their occurrence was slightly more frequent (4%) at 100 ppb exposure.

Ernst et al. (1977) warn that measurement of hatchability will not necessarily reveal the extent of pathological effects. Certainly effects at later larval or even juvenile stages might occur regardless of the responses that appear at hatching or shortly after hatching. Continued observation of larvae from adults exposed to oil during gametogenesis disclosed such a latent response, expressed as a reduction in growth and survival. Preliminary gas chromatographic analysis of gonadal tissue from exposed female winter flounder indicated that petroleum hydrocarbons were present in ovarian eggs at the time of spawning. These petroleum hydrocarbons, accumulated during gametogenesis or gamete maturation, were probably responsible for the observed latent impact upon the larvae. Changes in larval metabolism and absorption and utilization of yolk lipids and lipoproteins could certainly precipitate the effect of hydrocarbons stored in yolk. The contamination of sperm during spermatogenesis could contribute to this latent effect, but we suspect hydrocarbons present in eggs to be principally at fault. However, the particular stages of oogenesis when transport of hydrocarbons or hydrocarbon metabolites from serum into the eggs would be most serious are not known.

Eggs exposed during gametogenesis were selected for extended studies partly because exposure at this stage could have potentially large consequences. If adverse responses occured only after direct exposure of gametes, eggs, or larvae, then the impace of environmental contamination would be limited to those gametes, eggs, or larvae deposited or hatched in the contaminated area. However, if adults with maturing gametes were contaminated a potentially larger number of offspring could be affected, wherever spawning might occur. Saila (1961) estimated that a female flounder (1000 g) produces 1.2 million eggs. Furthermore, Haedrich and Haedrich (1974) provided evidence that winter flounder will inhabit as readily as avoid a chronically polluted environment. While numerous factors such as depuration rates could influence the ultimate extent of damage it seems likely such affects could occur in the field. Assessment of this aspect of

pollutant damage has been little explored. Struhsaker (1977) did, however, show that Pacific herring (Clupea harengus pallasi) exposed to 800 ppb benzene, very high levels, for 48 hours prior to spawning exhibited adverse responses including mortality of ovarian eggs, embryos, and larvae.

The absolute values of egg and larval oxygen consumption (µl O_2/organism/hr) increased exponentially with age but no consistent differences between treated and control animals were observed. However, oxygen consumption on a unit weight basis (µl O_2/µg dry wt/hr) (Figure 9) exhibited a trend which was inversely related to the observed trend in growth. This is similar to the findings of Laurence (1975) that the weight-specific O_2-consumption of winter flounder larvae decreases with increasing size. However, we also found variation among groups of larvae from different females exposed during gametogenesis, with a sequence of decreasing oxygen consumption coefficients similar to the sequence of decreasing growth coefficients. Restated, larvae having slower growth rates, e.g. those from exposed female 306, also consumed more oxygen per unit weight. This may reflect a diversion of energy from growth to metabolic processes involving stress due to oil exposure. Eldridge et al. (1977) offered a similar explanation for results obtained with herring eggs exposed to benzene, although in that study exposure was direct. The possibility exists that differences we see between groups of larvae may be genetic, yet this remains to be determined.

Although effects were evident on embryos and larvae exposed directly or parentally, there were no effects on several aspects of hepatic function of the exposed females that spawned these. The apparent lack of induction of cytochrome P-450 mixed-function oxygenases could well be temperature-related. The temperature in these experiments was extremely low, and reduced response of induction of other enzymes in fish at cold temperatures has been reported (Yamauchi et al., 1975). However, it could also be that the concentrations of any strong inducers in the oil, or in the tissue, were too low to stimulate induction, particularly at the low temperature.

Effects on hepatic ligogenesis, or on TCA cycle activity in other tissues, have been noted in some fish exposed to similar levels of oil (Stegeman and Sabo, 1976). The fact that no such effects were observed here need not be surprising. Again, the levels of oil were very low, and so was the temperature. Moreover the responses of intermediary metabolism to foreign compounds could vary markedly from species to species. Even within one species the responses could appear as a stimulation or a depression depending on a host of other factors.

The concentrations of aromatic hydrocarbons in the livers of exposed fish varied, ranging about 15 ppm. Extended exposure at 100 ppb oil did not result in higher concentrations and this could be due to subtle differences in such factors as rate of metabolism of hydro-

carbons or perhaps the rate of mobilization in the liver and incorporation into ovarian eggs.

An important aspect of these results is that significant deleterious effects on reproductive success may occur even though apparent hepatic function of the adult undergoing identical exposure appears unchanged. It would seem this can happen at very low levels of exposure, and the results have important implications for the value of certain types of monitoring for effects. Laboratory studies such as this one do not demonstrate that similar oil contamination, either acute or chronic, will have a similar impact in the field. Well integrated field and laboratory studies are necessary to do this. However, coordinated multidisciplinary studies like the present one can indicate where and how effects might occur, and aid in designing studies to define cause and effect in low level contamination.

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Table 1. Exposure times, concentrations, weights and lengths for female fish used for larval growth and survival experiments.

Tag #	Weight g	Length mm	Exposure				
			Dates	Duration (days)	Concentration ppb Mean±S.D.		Range
310(C_2)	620	355		0	0		
X_1(C_3)	-	-		0	0	Biogenic HC only	
X_2(C_5)	-	-		0	0		
108	635	363	12/1-13/3	75	90±30		50-190
109	918	400	12/1-14/3	76	90±30	nominal	50-150
112	785	385	12/1-13/3	75	90±30	100	50-190
306	387	295	4/3- 6/4	33	80±40		40-190
314	516	325	4/3-14/3	10	9±7	nominal	3-19
325	432	307	4/3-14/3	10	9±7	10	3-19

Table 2. Hydrocarbons Identified in Oil and Tissue Samples by GC-MS

Peak Number	Compound
1	C_2 Benzene
2	C_3 Benzene
3	C_3 Benzene
4	C_4 Benzene
5	C_4 Benzene
6	C_1 Naphthalenes
7	C_2 Naphthalenes
8	C_3 Naphthalenes
9	Phenanthrene
10	C_1 Dibenzo Thiophene
11	C_8 One Ring Cycloalkane
12	C_{10} One Ring Cycloalkane
13	C_{10} Branched Alkane
14	C_{11} Branched Alkane
15	C_{10} Two Ring Cycloalkane
16	Pristane
17	Phytane

Table 3. Concentrations of Total Hydrocarbons in Winter Flounder Tissue.

Tissue(N)	Dose	Time	Fraction	Concentration
Liver (2)	0	--	Aliphatics Aromatics	N.D.
Liver (2)	10 ppb	31 days	Aliphatics Aromatics	Trace 0.6 ppm
Liver (2)	100 ppb	33 days	Aliphatics Aromatics	Trace 21.9 ppm
Liver (3)	100 ppb	75 days	Aliphatics Aromatics	1.6 ppm 13.4 ppm

Table 4. Hepato-somatic index, % lipid and hepatic acetate-1-^{14}C metabolism in female winter flounder.

Nominal exposure	Sampling period (N)	$\frac{\text{Liver weight}}{\text{Body weight}} \times 100$	Liver lipid (%)	$\frac{^{14}C\text{-lipid}^{a}}{100 \text{ mg tissue}}$	$\frac{^{14}CO_2{}^{b}}{100 \text{ mg tissue}} \times 10^{-3}$
Control	January (8)	2.53 ±0.39	2.64 ± .78	5001 ± 2958	17.6 ± 11.2
	Feb-March (8)	2.23 ±0.45	3.76 ± .98	6288 ± 4726	10.9 ± 7.4
10 ppb	January (9)	2.26 ±0.25	2.49 ± .84	7700 ± 4152	22.5 ± 10.1
	Feb-March (6)	1.76 ±0.69	2.80 ± .96	8098 ± 5511	14.9 ± 9.5
100 ppb	January (7)	2.59 ±0.17	2.3 ±1.0	5079 ± 2738	22.3 ± 7.6

Valves are $\pm$ 1 Standard deviation

a) CPM of ^{14}C-lipid extracted from tissues following 2 hr. incubation, normalized to 100 mg wet wt. tissue.

b) CPM of $^{14}CO_2$ respired during 2 hr. incubation.

Table 5. Hepatic microsomal protein mixed-function oxygenase and cytochrome P-450 in female winter flounder.

Nominal exposure	Sampling period(N)	mg microsomal protein / g liver	Benzo[a]pyrene hydroxylase (units mg^{-1})[a]	Aminopyrine demethylase (units mg^{-1})[b]	Cytochrome P-450 (nmol mg^{-1})[c]
Control	January (8)	24.2 ± 4.0	11.1 ± 5.4	34.7 ± 25.8	0.144 ± 0.039
	Feb-March (8)	26.1 ± 3.0	22.0 ± 14.9[d]	34.3 ± 22.1	0.144 ± 0.042
10 ppb	January (9)	26.7 ± 5.1	14.7 ± 15.0	32.2 ± 8.4	0.139 ± 0.051
	Feb-March (6)	22.8 ± 2.9	28.1 ± 26.0	39.2 ± 8.7	0.204 ± 0.062
100 ppb	January (7)	24.5 ± 7.2	9.1 ± 6.0	29.5 ± 15.2	0.108 ± 0.022

Valves are $\pm$ 1 standard deviation.

a) Units equal picomoles 3-OH-benzo[a]pyrene equivalents produced per minute.

b) Units equal nanomoles formaldehyde produced per hour (normalized).

c) Units equal nanomoles of cytochrome P-450.

d) Significantly different from January Samples at $P \leq 0.05$.

Table 6 Acetate-1-^{14}C metabolism and benzo[a]pyrene hydroxylase in female winter flounder[a].

Sample (N)	^{14}C-lipid[a] / 100 mg tissue	$^{14}CO_2$[b] x 10^3 / 100 mg tissue	Benzo[a]pyrene hydroxylase units/mg[c]	Benzo[a]pyrene hydroxylase units/nmol P-450[d]
14-15 day exposure				
control (5)	3492 ± 1287	14.3 ± 9.1	9.3 ± 6.3	72.2 ± 40.0
10 ppb (6)	5758 ± 2964	30.2 ± 12.0	14.1 ± 11.2	76.9 ± 50.8
100 ppb (5)	4250 ± 2862	21.3 ± 7.2	8.5 ± 7.2	76.5 ± 50.1
50-57 day exposure				
control (5)	7401 ± 5176	9.5 ± 5.0[e]	27.7 ± 12.8[e]	243.9 ±149.1[e]
10 ppb (3)	5050 ± 1059	9.7 ± 7.1[e]	21.3 ± 22.6[e]	216.0 ±208.0[e]

Values are ± 1 standard deviation.

a-c) Units are as in Tables 1 and 2.

d) Units equal picomoles 3-OH-benzo[a]pyrene equivalents produced per minute, per nanomole cytochrome P-450.

e) Significantly different from 14-15 day samples at P≤ 0.01.

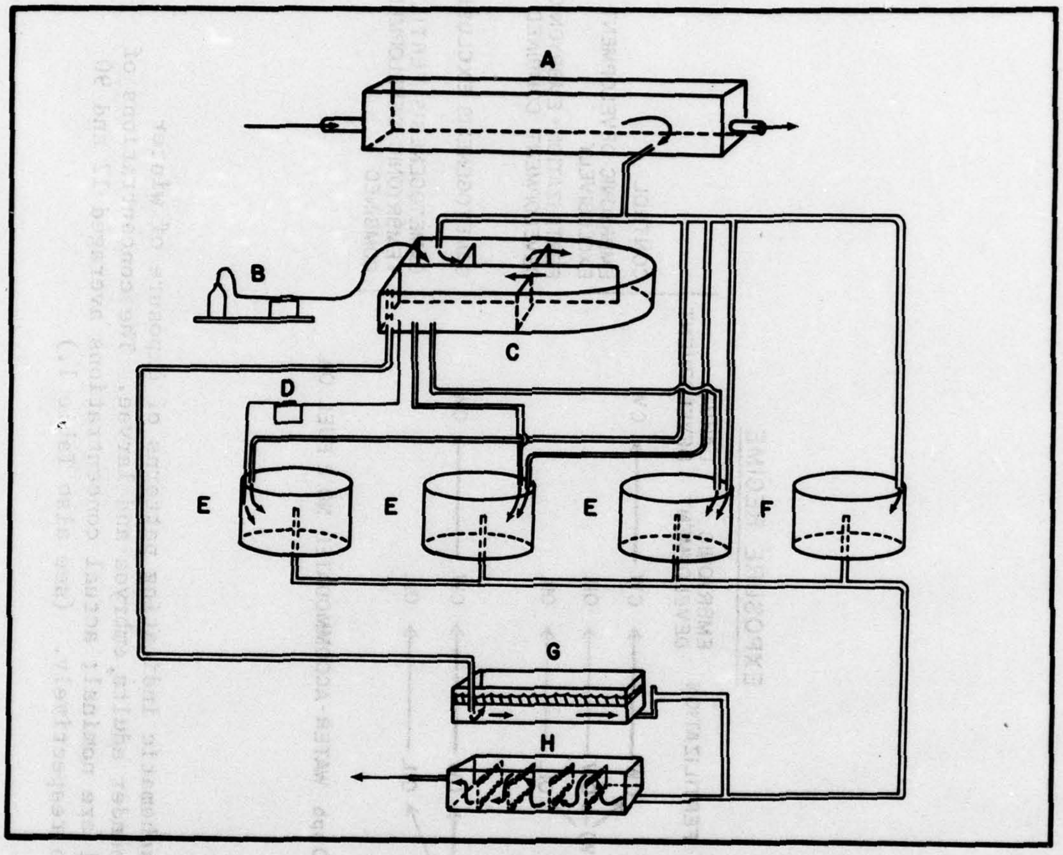

Fig. 1 Continuous flow dosing apparatus for water accommodated fractions of oil (WAF). A-seawater reservoir; B-oil supply and peristaltic pump; C-peristaltic pump for low concentrations; E-experimental dosing tanks; F-control tank; G-waste oil collection chamber; H-filter box with acrylic fibers (from Hyland et al., 1977).

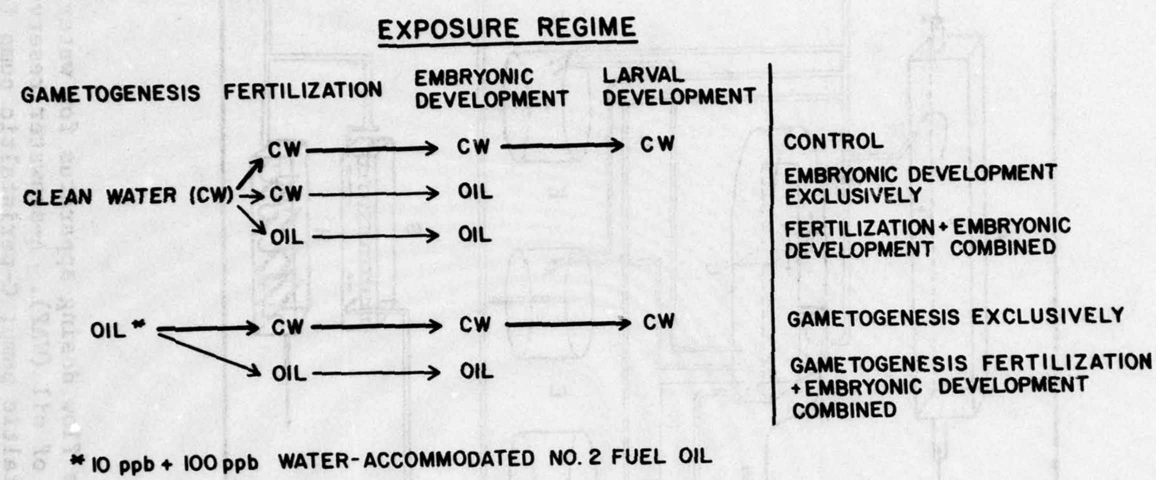

Fig. 2 A schematic indicating patterns of exposure of winter flounder adults, embryos and larvae. The concentrations of oil are nominal; actual concentrations averaged 12 and 90 ppb respectively. (see also Table 1.)

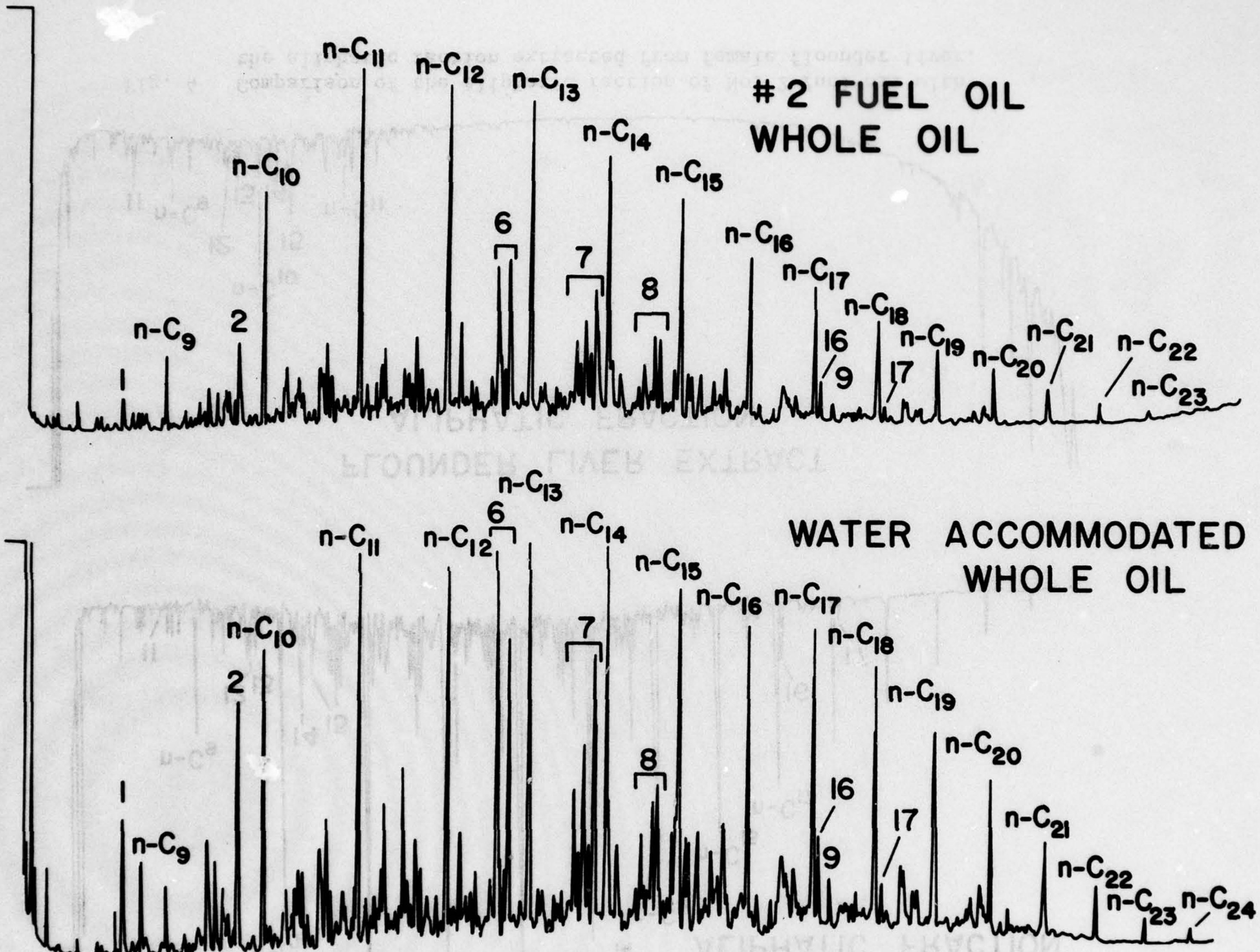

Fig. 3 Gas chromatograms of the whole No. 2 fuel oil (upper) and the CCL_4-extractable hydrocarbons of the water-accommodated fraction (WAF) (lower).

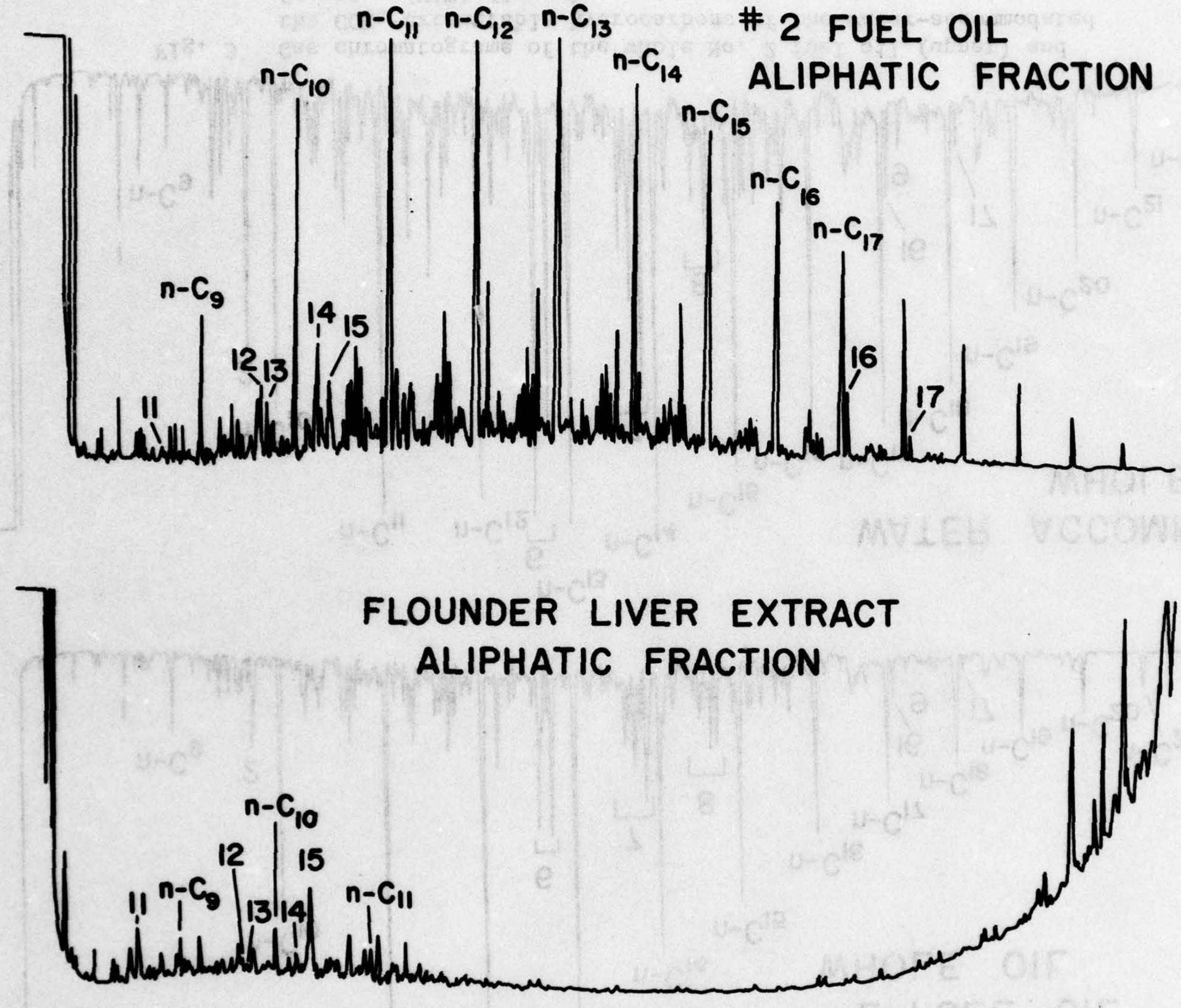

Fig. 4 Comparison of the aliphatic faction of No. 2 fuel oil with the aliphatic faction extracted from female flounder liver.

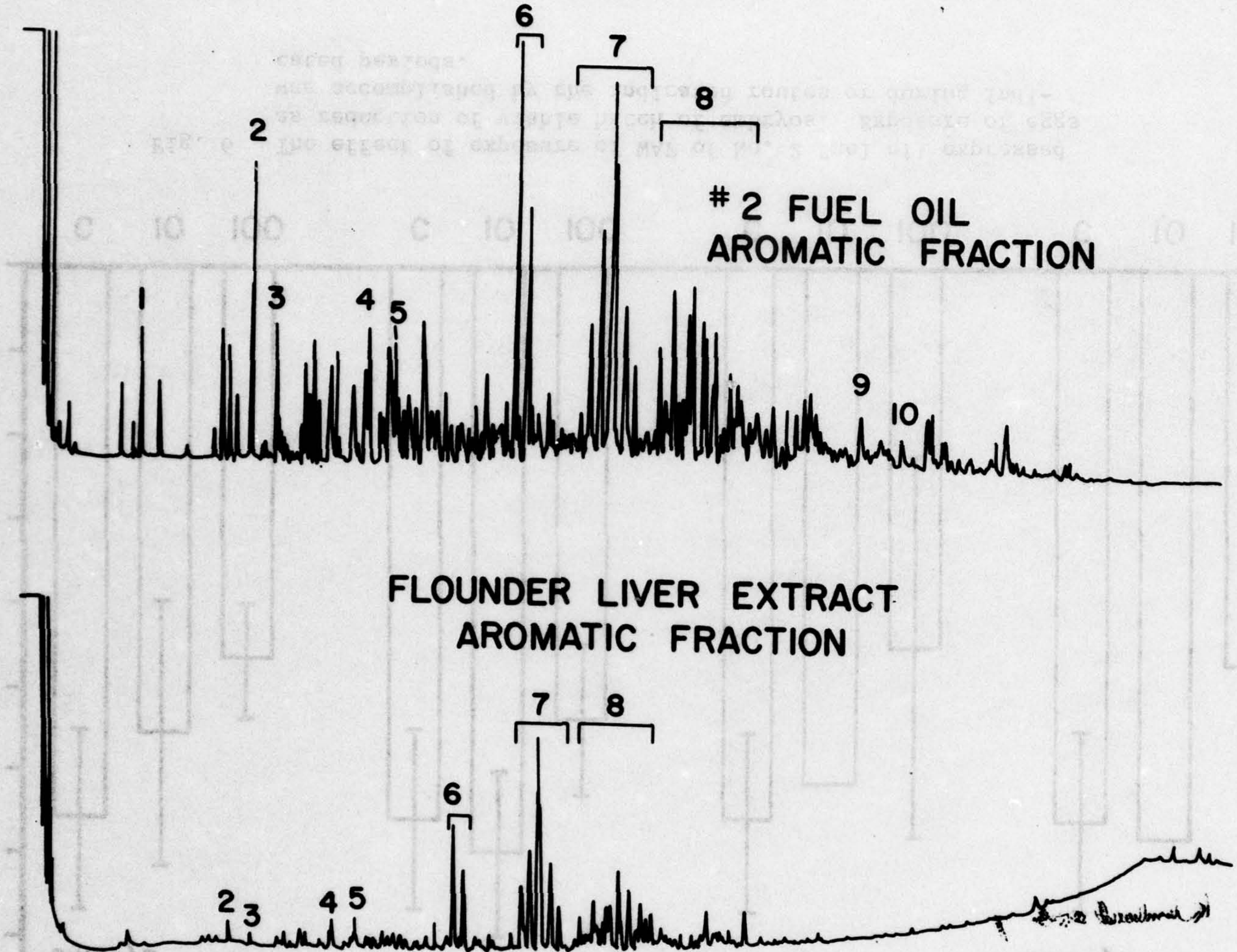

Fig. 5 Comparison of the aromatic faction of No. 2 fuel oil with the aromatic faction extracted from liver.

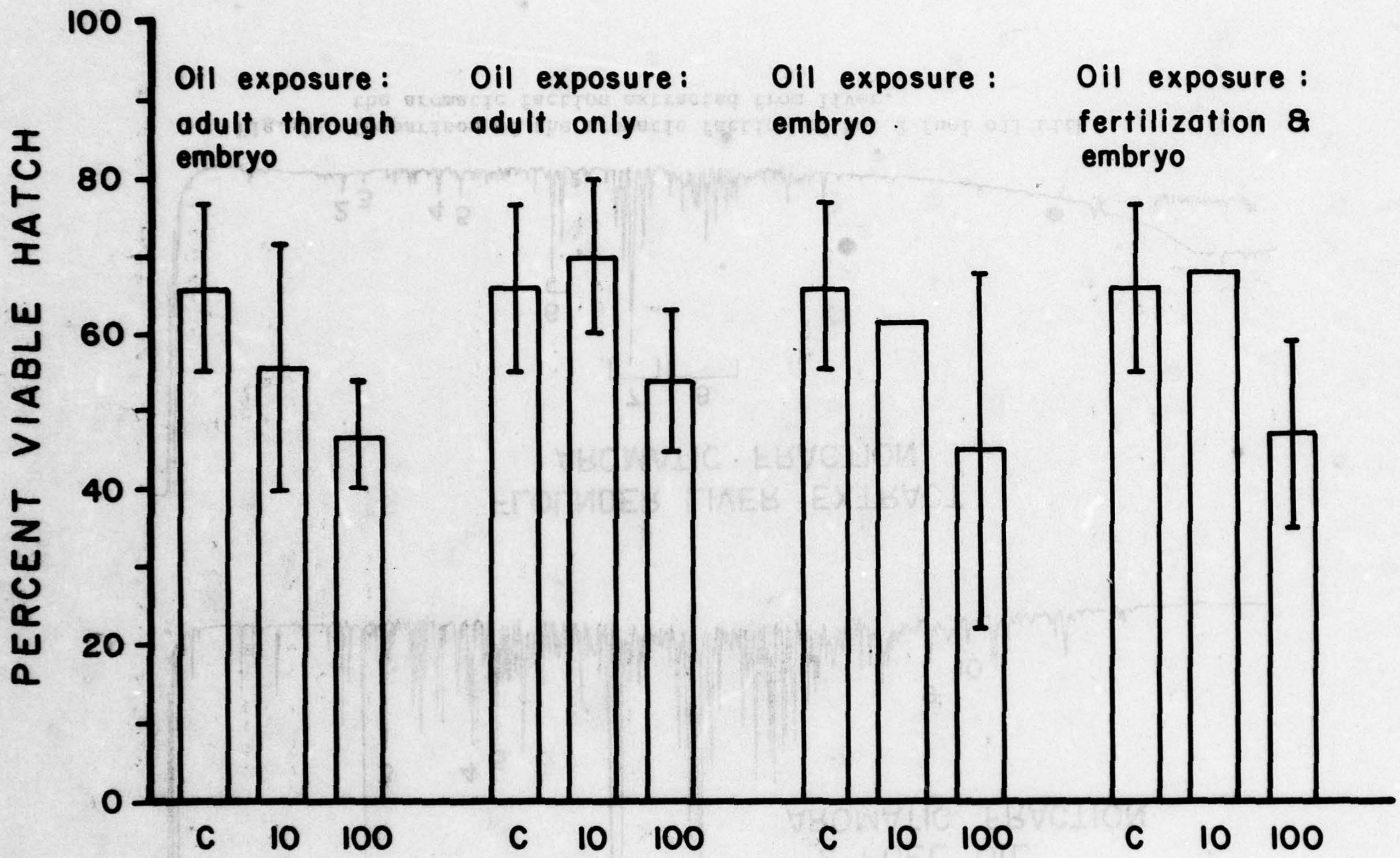

Fig. 6 The effect of exposure of WAF of No. 2 fuel oil expressed as reduction of viable hatch of embryos. Exposure of eggs was accomplished by the indicated routes or during indicated periods.

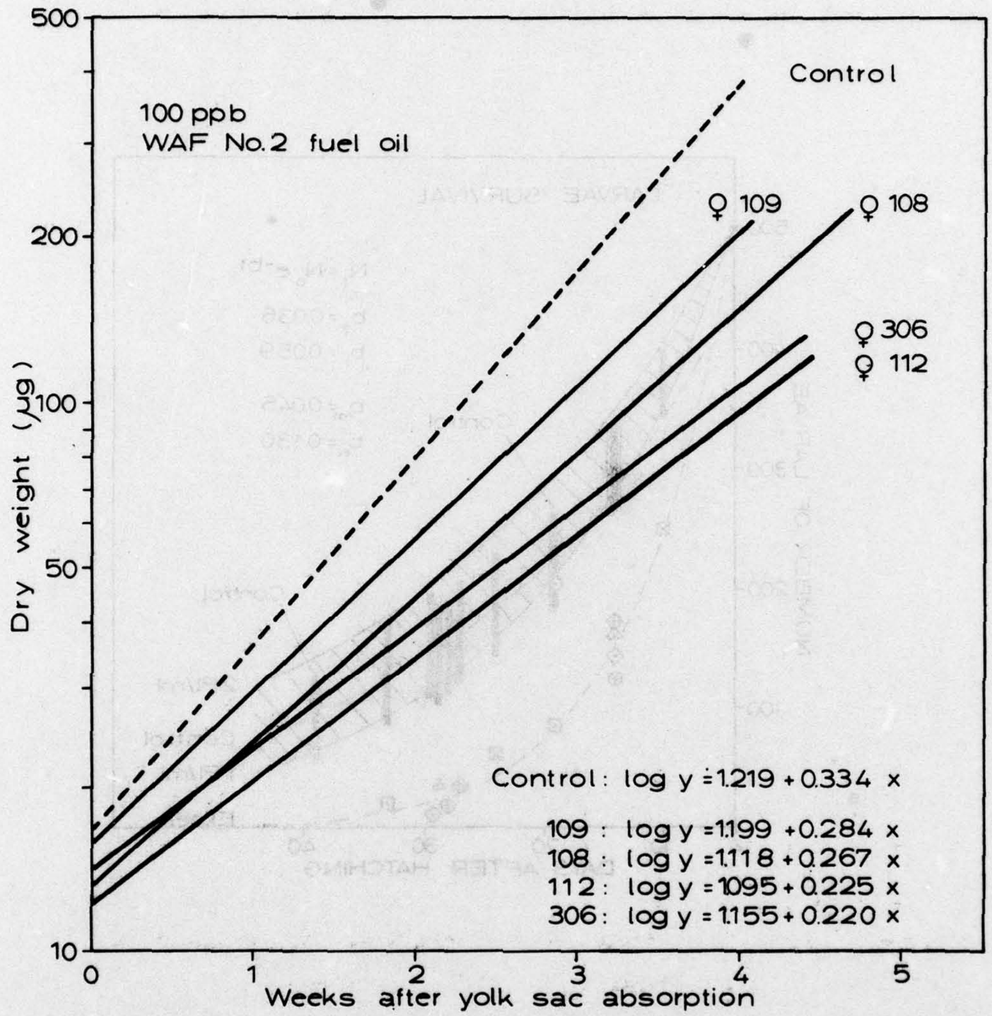

Fig. 7 Growth regression lines for larvae of winter flounder that had been exposed to WAF of No. 2 fuel oil during gamete maturation only. Correlation coefficients r are 0.960, 0.992, 0.943, 0.928, 0.968, 0.938, and 0.928 for progeny of control females, females 109, 108, 112, 306, 314, and 325 respectively.

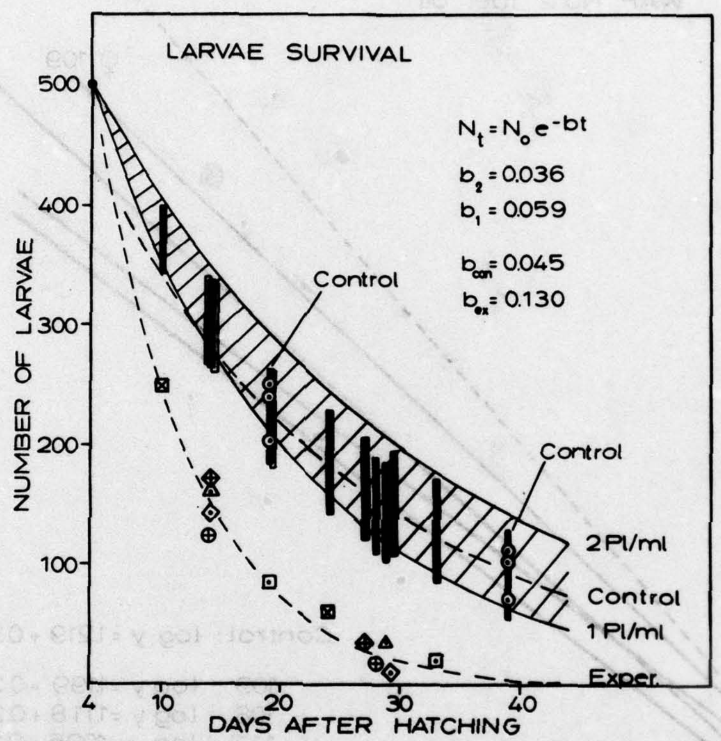

Fig. 8 Survival of winter flounder larvae of parents which had been exposed to WAF of No. 2 fuel oil (10 and 100 ppb). Shaded area shows theoretical survival at food density of 1 and 2 plankters/ml. The vertical bars show expected number of survivors. Deviation from range of shaded area was due to samples being taken every week. Symbols below bars give observed numbers of survivors of parentally influenced larvae.

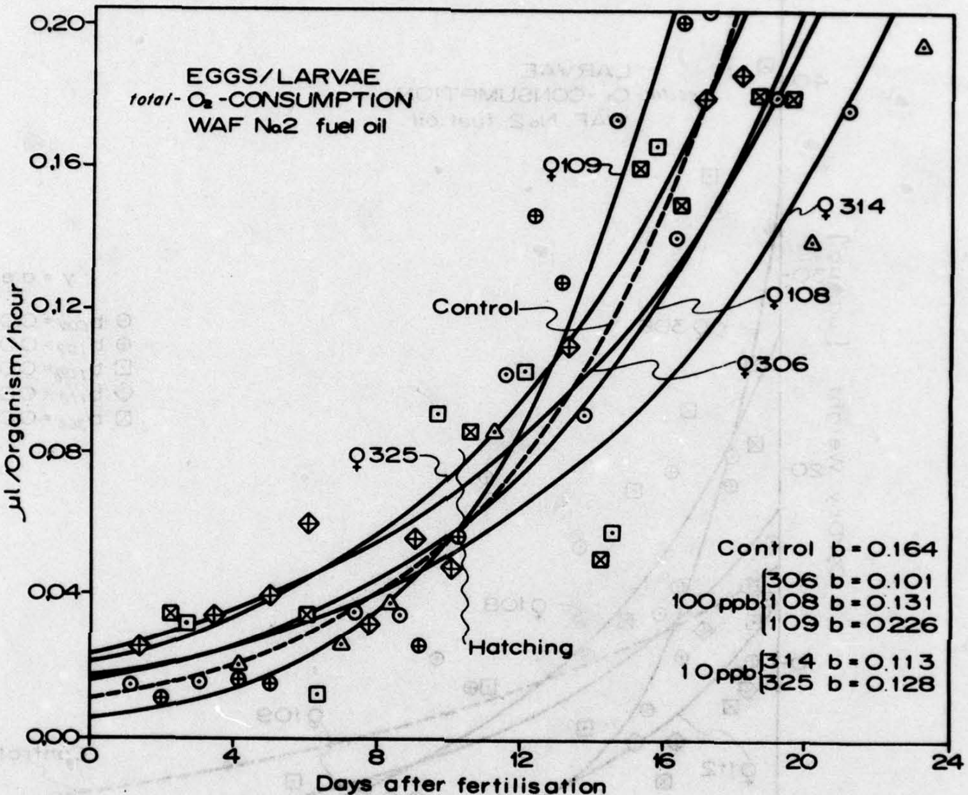

Fig. 9 **Total oxygen consumption of eggs and early larvae from parents exposed to WAF of No. 2 fuel oil. Hatching occurred at day 10. Correlation coefficients r are: 0.967, 0.927, 0.764, 0.963, 0.947, 0.919 for progeny of control females, and females 306, 108, 109, 314, and 325 respectively.**

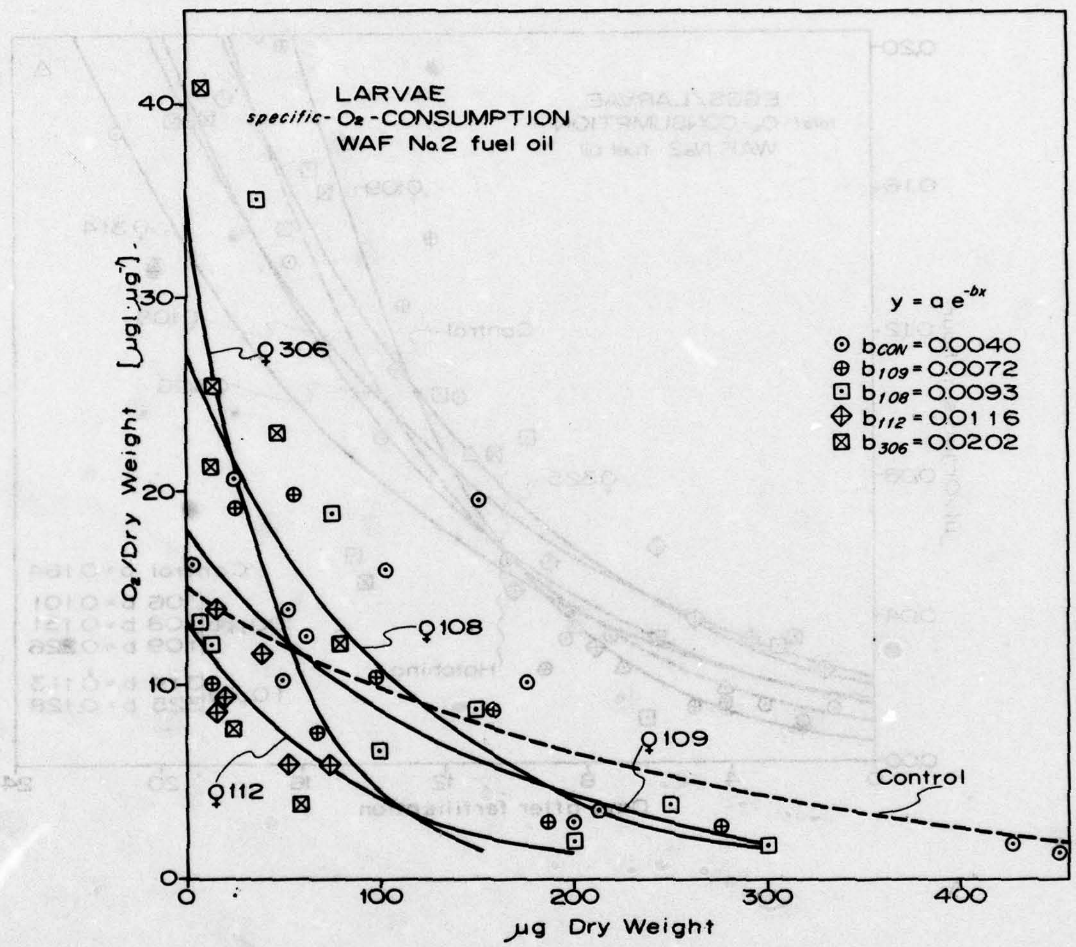

Fig. 10 Specific oxygen consumption of winter flounder larvae per weight unit. The correlation coefficients for the calculated regressions are: 0.791, 0.717, 0.814, 0.765, and 0.713 for progeny of control females, and females 109, 108, 112, and 306. The intercepts do not represent valid values for reasons given in the text.

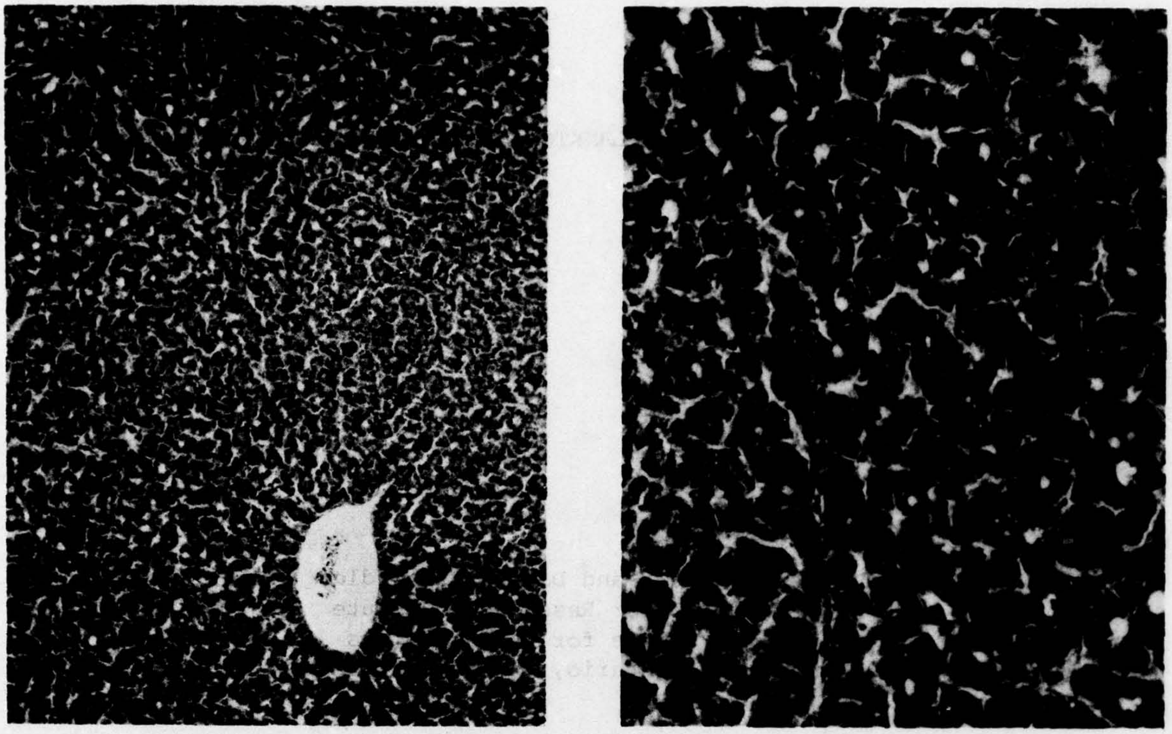

Fig. 11 Normal appearing liver from *Pseudopleuronectes americanus* female exposed to water-accommodated fraction of No. 2 fuel oil. Exposure time was 33 days. Mag. 25 x (left) and 160 x (right) H. + E. (printing enlargement not considered).

IMPACT OF CRUDE OIL ON PLANKTONIC FRESHWATER ECOSYSTEMS

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During the winters of two field seasons, a series of five oil spills were carried out in artificial ponds near Ottawa. The types and amounts of the crude oils spilled varied. The biological components of phytoplankton, protozoa, zooplankton and bacteria were monitored fortnightly. It was found that the bacteria populations of the treated ponds were enhanced while there was an ice cover and the enhancement increased after the ice had melted. In addition, the zooplankton populations diminished only after the ice cover melted, and the phytoplankton, protozoa and water chemistry parameters were influenced by the presence of oil.

INTRODUCTION

Accidental spills of oil and its products occur on a vast scale, both in the marine and freshwater environments. Considerable research effort has been expended on the effects in marine environment (Fate and Effects of Oil Working Group 1977) but effects on the freshwater environments have received relatively less attention despite the fact that the volume of oil introduced into the North American freshwaters (Ross 1977) is nearly equal to that spilled in the offshore North American marine environment (U.S.C.G. 1975). Because of the intense demands for high quality freshwater supplies for aquaculture and fishing, drinking water, recreation and industry, and because of the importance of maintaining ecologically-healthy environments, the effects of oil pollution in freshwater need to be studied more extensively. Some of the results of studies on marine environments, of course, are applicable to freshwater situations but major differences in physical, chemical, geological, climatic, and biological conditions require that, for the most part, the various freshwater situations be studied separately.

Our approach to studying freshwater oil-pollution effects involved the use of large, open, polyethylene-lined artificial ponds (Scott *et al*. 1975; Shindler *et al*. 1975). These were selected for the experiments because: (a) they were open and would be affected by natural conditions (including the winter climate) which are impossible to duplicate in the laboratory; (b) the experiment could be replicated with up to four ponds per season and comparisons made between treatments; (c) they would permit experimental manipulation of the oil in the environment with little risk of environmental contamination, and (d) they would be easy to clean up after each experimental series.

We report here the ecological trends noted in experiments begun in the winters of 1974 and 1975, with each of the two series followed

for about a year. Some results from aspects of previous studies have been published elsewhere (Scott et al. 1975; Shindler et al. 1975).

EXPERIMENTAL

Experiments were conducted in four man-made ponds located 32 km northwest of Ottawa, Ontario. Each pond was doubly-lined with 6 mil polyethylene sheeting. In both the 1974 and 1975 experimental series, ponds were filled simultaneously during October with water from the adjacent Ottawa River. The ponds were filled to a depth at the centre of 1.6 m; the surface of the ponds measured 15.6 x 7.2 m (estimated volume, 150 m^3). The ponds remained undisturbed for about four months before the oilspill experiments were begun.

Oil was introduced into the ice and snow-covered ponds during mid-winter. In 1974, Norman Wells crude oil was used in the spills; in 1975 either Norman Wells or Pembina crude oil was used. Ponds in which no oil was added served as controls. The amounts and types of oil spilled are listed in Table 1. Properties of the crude oils and physical and chemical changes during experiments have been described previously (Scott et al. 1975; Snow et al. 1975; Scott 1975).

Using a 2.1 ℓ Van Dorn sampler, water for phytoplankton analyses during the summer were taken from a 0.5 m depth and during the winter, from 0.25 to 0.75 m below 0.7 m thick ice; subsamples were fixed and preserved in Lugol's solution. Identifications and numerical estimates of the phytoplankton were made using a Ütermohl counting chamber with an inverted phase-contract microscope. Samples which contained diatoms were treated with HF, mounted, and identified separately. Occasionally fresh, unfixed samples were taken and examined and the identifications checked against those which were preserved. The phytoplankton have been divided for analytical convenience into six taxonomic divisions (Smith 1950), shown in Fig. I. Included in the general phytoplankton classifications were closely related achorophyllous protozoans (Fig. I), subdivided into three divisions. Zooplankton were collected in a 60 mesh net from a vertical haul, transferred to 5% formalin, then enumerated and identified microscopically.

Samples for enumeration of bacteria were collected aseptically from about 0.6 m below the surface of the water or ice, using a specially designed sampler (Shindler et al. 1978). After appropriate dilution the samples were inoculated on media solidified with agar, incubated at or near in situ pond temperatures and the resulting colonies counted. The general media for heterotrophic enumerations were Poindexter's (Poindexter 1964) and CPS (Collins et al. 1962) media, 3 g/ℓ organic nutrients; both gave similar counts. The enriched media were plate count agar (8.5 g/ℓ organic nutrients and King's B medium 30 g/ℓ organic nutrients) which were used in the 1974 study previously reported

Water chemistry samples were taken from the same locations and depths as the phytoplankton samples. Analytical methods were adopted from the APHA Standard Methods (American Public Health Ass. 1977) for

the 1974 studies, and from the Canadian Standard Methods (Analytical Methods Manual 1974) for the 1975 studies. Diurnal dissolved oxygen measurements were made with a YSI model 51A oxygen meter and probe (Yellow Spring Dust. Co., Yellow Springs, Ohio).

RESULTS

1974 Experiments

Phytoplankton and protozoa enumerations show that in the period of ice cover (until mid-April) and into early spring (May) all ponds were dominated by protozoa with Chlorophyta and/or Cryptophyta also numerous (Fig. 1). Later in the summer (June - September) the ponds were dominated by Chlorophyta with occasionally Cyanophyta more numerous. Other algae, of course, were present in all ponds prior to addition of the oil but disappeared in Ponds I and II upon oil addition. Small numbers of Pyrrophyta were constantly present in the control pond, but were absent in Pond I and appeared in Pond II during late summer. Euglenophyta were also found in significant quantities in Pond I by late summer.

The populations of the algae and protozoa as enumerated microscopically are shown in Fig. 1. After mid-April the oiled ponds had generally higher densities of algae than the control pond. The first marked increases in the algal populations occurred during May. During the spring "bloom" period (May), relatively few types of algae in extremely large numbers dominated the microbial populations of the ponds. In the control pond, Zoomastigophora, Chlorophyta and Cyanophyta dominated; in Pond I a similar pattern existed; in Pond II more Chlorophyta but relatively fewer Zoomastigophora were observed. During the late summer blooms in all the ponds were dominated by Chlorophyta. Scenedesmus made up 80% of the total algae in the control pond during August; Dictyosphaerium made up more than 90% in Pond I; Gonium was the major genera in Pond II at that time but only made up 15% of the total, which included representatives of other divisions and other Chlorophyta found also in the control pond and Pond II. The various genera of chlorophyta contributing to the blooms are listed in Appendix A.

Zooplankton quantification and identification are given in Table 2. All ponds contained reasonable populations of zooplankton during and just after the period of ice cover (April 19). After this time, however, the populations of zooplankters in Ponds I and II were reduced drastically relative to the control pond. The populations in Pond II increased somewhat in late summer but no such recovery was observed in Pond I.

Bacteria enumerations on various bacteriological media and identification of the dominant genera in each of the ponds have been reported (Shindler *et al*. 1975). During the winter, bacterial populations reacted to the addition of oil to the water beneath the ice. In the oil under ice experiment (Pond II) there were only two predominant

genera by April in contrast to a greater diversity, at least six predominant genera, in the control pond and in the oil on ice pond (I). At this time a higher proportion of the heterotrophic bacteria in Pond II were able to grow on the "rich" (>8 g/ℓ nutrients) bacteriological media in comparison to Pond I or the control pond. Shortly after the ice melted which allowed the oil in Pond I to contact the water, marked population shifts occurred and the proportions of bacteria able to grow in the rich media also subsequently increased. The presence of oil caused a selection for the bacteria which were adapted to grow in an environment enriched with organic nutrients. During the rest of the spring and throughout the summer, the presence of oil was associated with increased bacterial counts on all media: Pond I > Pond II > Control.

Water chemistry parameters taken over the monitoring period are listed in Table 3. From the concentrations of the magnesium and calcium ions (1-2 ppm and 2-3 ppm, respectively), the water in the ponds may be considered as soft water. When there was an ice cover, concentrations of these ions were twice that of the concentrations during the ice-free period. The pH in the control pond was generally greater than neutral during the summer and fall, while pH in Pond II was either slightly basic or slightly acidic. In Pond I, the pH of the water was generally acidic, reading a low value of 4.9 at the end of July. The alkalinity in the control pond generally ranged from 10 to 20 ppm ($CaCO_3$) and was slightly lower in Pond II. Pond I, however, had values about 1 ppm after June 28. Dissolved oxygen (taken at 10 - 11 a.m.) in Ponds I and II indicated saturation until July, with values generally higher in the control pond. After that, values in all ponds generally decreased, with Pond I having the largest decrease and the control, the least.

Oil analysis of the Norman Wells crude on the surface of the ice of Pond I over the winter showed that a portion of the low boiling components evaporated while the temperature was cold, but not more than 35% of the oil was lost. This was estimated by using the n-alkanes as flags in chromatograms of the oil (Scott et al. 1975; Scott 1975). At the time of spring thaw, the oil chromatograms indicated the evaporation of volatile fractions continued slowly until there were only traces of tridecane present. No significant changes were noted in chromatograms of the oil collected after this time. The oil in this pond had formed a thick layer, about 1 cm thick which covered about half the water surface of the pond. The top surface of the oil layer was shiny dark brown, and the oil in direct contact with the water formed a light-brown or tan mousse. The oil remained in this state throughout the summer.

For the oil under ice experiment in Pond II, no oil was found in or around the sampling hole during the period of ice cover. Once the oil was exposed for several hours at spring thaw, the chromatograms showed traces of n-heptane which indicates the presence of volatile components. This was in contrast to the situation in Pond I where the oil had evaporated substantially while on the surface of the ice. Within three days after being exposed, the chromatograms of samples of the exposed oil were identical to those of the weathered oil in Pond I.

Winds moved the oil around both ponds. Occasionally smaller parts would break off from the larger slicks, and further fragmentation resulted in the formation of tar-balls (about 102 cm^3 volume) which eventually sank. No marked formation of a chocolate mousse (water in oil emulsion) was noticed in Pond II.

1975 Experiments

Phytoplankton and protozoa composition of the ponds is shown in Fig. 2. Zoomastigophora, Chrysophyta and Chlorophyta were the major plankters considered in this section while there was ice cover. No marked changes in populations were obvious immediately after the oil was added, under the ice. After spring thaw (mid-April) Chrysophyta and Cyanophyta were more abundant in the control pond than in the others. Pond V (90 ℓ Pembina oil) had a continuous content of Zoomastigophora from mid-May until mid-September, with Ponds IV and III (90 and 45 ℓ Norman Wells oil, respectively) having lower populations. The control pond had only minor Zoomastigophora populations.

The results of the phytoplankton and protozoa enumerations are also shown in Fig. 2. During the spring blooms (May) the greatest number of algae were found in the control pond and Pond III. The blooms were predominantly Cyanophyta (*Anabaena* sp.). The May populations in Ponds IV and V were lower and the blooms were composed of both Zoomastigophora and Cyanophyta. The late summer pulses of algae in the control pond were also very large compared to the other ponds, with Cyanophyta (*Anabaena* sp.) dominant in August and Chlorophyta (*Ankistrodesmus*) dominant in October. The August blooms in the other ponds were predominantly Chlorophyta, as follows:

Pond III : *Scenedesmus* and *Ankistrodesmus*
Pond IV : *Kirchneriella*
Pond V : *Scenedesmus*

These are taken from Appendix B. In contrast to the control pond, the oiled ponds did not have a major October pulse.

Zooplankton populations for the 1975-6 field season, which are listed in Table 4 show that all ponds have variable, but comparable populations during the period of ice cover. After that, the control pond generally maintained higher populations of zooplankters than any of the treated ponds. Of the treated ponds, Ponds IV and V generally had lower populations of zooplankton than Pond III.

Bacteria counts on low and high nutrient media indicated that there was a significant initial increase in bacteria populations shortly after the oil was introduced under the ice (Shindler *et al.* 1978). This increase continued throughout the summer period; recoveries from Ponds IV and V were similar and generally a factor of 10 greater than in the control pond. Values from Pond III were approximately intermediate between the control pond and those of Ponds IV and V. As noted in the 1974 results, the proportion of bacteria able to grow in rich media was

higher in the oiled ponds than in the control. In November and December, as winter approached and the water became cooler, the bacterial populations in the treated ponds decreased. 1975-76 winter enumerations showed that the differences between the oiled and control ponds disappeared. Samples taken 1-1/2 years after the spills during the spring of the following season indicated, however, that the differences between the oiled ponds and the control were re-established.

Water Chemistry data are contained in Table 5. Alkalinity values in Ponds IV and V were generally less than those recorded in the control pond. In September, Pond V had less than one ppm total alkalinity reported as $CaCO_2$. Values in Pond III were similar to those in the control pond. The pH in Pond V was generally slightly less than observed in the control pond. Under the ice during the winter dissolved O_2 (D.O., Winkler method) values in all ponds were at saturation levels. During May, the D.O. levels in Pond V were below saturation at the times the samples were taken (10-11 a.m.). The D.O. values in Pond IV were not as low as those found in Pond V, but they were not as high as those observed in the control pond.

During the summer, diurnal changes in D.O. were measured (Fig. 3). Measurements were taken just past sunrise, after the respiratory O_2 consumption during the night reduced the value to a minimum and just before sunset, after the photosynthetic O_2 evolution elevated the value to the maximum. The control pond remained at supersaturated values throughout June and July, and after that only the morning values were below saturation. Pond V frequently had both sunrise and sunset D.O. values below saturation. In Ponds III and IV the sunrise values were below saturation, with the values in Pond IV being lower than in III. In both ponds, the sunset values were above saturation from June through to September.

Appearance of the ponds and oils was dependent on the amount and type of oil used. The control pond water remained much less turbid than that of the oil ponds. During the spring and summer the water was translucent; during the autumn it had a slightly yellow-green colour. After June, the water in Pond V was brown and turbid and one could not see more than two decameters through the water column. The waters of Pond IV were a bit clearer but the bottom (1.5 m) usually was not visible. The water in Pond III was slightly less turbid than that of Pond IV.

The state of the Norman Wells oil in Pond IV resembled that in Pond II (1974, 90 ℓ spill). It was a soft solid mass, dark brown or black on the air surface and light tan on the water-oil interface. Small lumps would detach themselves from this mass and remain floating on the water surface. Oil on the water surface of Pond IV persisted until mid-July as a thick film but by then was lighter in colour (reddish-tan). After this time the oil broke up into successively smaller tan-coloured lumps and finally into 1 cm diamter balls, some of which eventually sank. Very little surface oil (approximately 1%) remained after mid-September but there was a noticeable sheen. In Pond III (45 ℓ Norman Wells oil) the formation of smaller balls occurred about one month earlier than in Pond IV, and comparatively less oil remained on the surface.

Pembina oil (Pond V) was darker and more resistant to fragmentation than Norman Wells oil. It became lighter in colour as the summer progressed but changed only from dark brown to brown. By September, considerably more of the original oil volume (90 ℓ) remained on the surface (estimated 35%) of the water.

DISCUSSION

The ultimate ecological effects of an oil spill in an aquatic system depends upon a great many factors. Of particular importance is the kind and amount of oil spilled in relation to the climatic, geochemical and limnological circumstances. In these experiments using artificial ponds, we simulated crude oil spills taking place during the Canadian winter. The shallow ponds were initially filled during the autumn preceding the spills with water from the Ottawa River, upstream from Ottawa, Ontario. At the point where the water was taken, the Ottawa River water quality was similar to what might be found in a eutrophic lake (30 - 40 μg/ℓ total phosphorus, 300 - 400 μg/ℓ total nitrogen; Ontario Ministry of the Environment, unpublished data). The ponds remained undisturbed until the winter when spills with two types of crude oil were performed.

During the two years of experiments described here, five ponds were treated with oil and two "controls" remained untreated for comparison. Ecological effects were followed for approximately one year after each of the spills. Observations of the plankton and on several chemical and biochemical measurements related to biological activity are reported here. The compromises involved in using ponds lined with polyethylene for making ecological observations as opposed to completely natural systems, undoubtedly effect the results. But the advantages of using replicated large systems far outweigh the disadvantages. Our results, we think, apply to oil pollution situations in ponds or quiescent embayments of larger water bodies which would not be likely to lose the polluting oil through water flow into and out of the area.

Oil was added to the ponds during the winter in each series while about 50 cm thick ice covered the ponds. No drastic changes in the zooplankton and phytoplankton populations were observed during the month or so after the spills while the ice cover remained (until mid-April). The only discernible changes which can be ascribed directly to the presence of oil occurred in the bacterial populations. Data from 1974 bacterial samples (Shindler _et al_. 1975) indicated that there were changes in the generic composition of heterotrophic bacteria during the winter after oil was spilled under the ice. Also, the proportion of bacteria able to grow in the high nutrient-rich media was higher in the oil-under-ice spills than in the control ponds or in the 1974 oil-over-ice experiment (Pond I). Bacteria, in contrast to the phytoplankton and zooplankton, reacted to the presence of oil under the ice.

The lack of noticeable effects on the phytoplankton and zooplanton during winter was surprising. In the cold water the physical

properties of the oils used may have been such that contact between toxic components and those sensitive organisms was minimal. Certainly, the volatile components of the oils did not evaporate extensively, i.e., the oils did not "weather" completely while trapped under the ice. Little information is available on the properties of oil under such conditions. When the ice melted, drastic effects on the biota became obvious. It is impossible to determine from these experiments whether critical damage was done while the oil was under the ice and only observed after spring melt, or if the effects were actually only important during and after melting.

The zooplankton populations in the oiled ponds were drastically reduced after spring melt. Cyclopoda and Calanaida were particularly affected (Tables 2 and 4) with an 80% or more population decrease in the oiled ponds vs. the control (1975). Cladocera and Cyclopoda could better tolerate the conditions in the pond containing 45 ℓ Norman Wells oil as compared to those in the other ponds containing even more oil. These effects probably depend upon many factors, including toxic substances in the water from the oils or from metabolic products, the absence of edible algae and possibly delayed effects from the winter period. Massive zooplankton mortality caused by oil and possible repercussions have been noted previously (Adams et al. 1975; Barsdate 1972).

The effects on the phytoplankton (Figs. 1, 2) were not as easy to interpret as those in the bacteria and zooplankton. Each pond was unique in terms of the distribution and variation over time of the algal populations. All the ponds showed similar general seasonal variations with minor increases in algal abundances in the spring and more marked increases ("blooms") in the autumn. In the 1974 experiments, the spring communities were dominated by Zoomastigophora with Cryptophyta and Chlorophyta; in 1975, by Crysophyta and Clorophyta. In both years' series, the phytoplankton populations shifted by late summer towards communities dominated by Chlorophyta and Cyanophyta.

The presence of oil indirectly or directly had interesting, although complex selective effects on the algae. For instance, during the autumn significant numbers of Euglenophyta were found only in oiled ponds. In the pond containing Pembina oil (Pond V), Zoomastigophora were prevalent during the summer of 1975, less abundant in Pond IV, and virtually absent in the other two ponds. The composition of the algal populations in Pond III (45 ℓ Norman Wells oil) was intermediate between Pond IV (90 ℓ Norman Wells oil) and the control pond; Pond III contained many of the types of algae found in each of the other ponds.

During the summers following the oil spills, the appearances of the ponds and the chemical data were indicative of the biological status. Water turbidity increased and dissolved oxygen decreased with dose of Norman Wells oil. The effects of turbidity, O_2, pH, etc., of Pembina oil were slightly greater than for an equivalent amount of Norman Wells oil. The chemistry of the oil-polluted system reflected particularly well the stimulation of heterotrophic respiratory activity. In spite of relatively higher chemical and biochemical oxygen demand values and total organic carbon values in the oiled ponds relative to the control

(1975 data not shown), the ponds did not become O_2 depeleted. The algal photosynthesis combined with the extent of O_2 diffusion indicated by the surface to volume ratio of the ponds appeared adequate to counteract the increased respiratory activity. Microbial oxidation of the oil is slow and would not be expected to cause rapid O_2 depletion of the ponds.

Weathered crude oils, either floating or sunken, persisted in these systems. The major material loss from the oil was the initial evaporative losses of the volatile components. Although the oil changed physically, we have no strong evidence that a great deal of oil was degraded. From gas chromatographic analyses of fractionated oils from the sediments collected at the end of the 1975 experiment (Shindler et al. 1978) it was noted that there were decreases in some of the alkane fractions, but that the bulk of the oil components remained undegraded.

The presence of oil in the aquatic system in significant amounts over several months could be expected to cause changes in algal populations, increases in heterotrophic bacteria, drastic decreases in zooplankton and changes in associated chemical measurements. Oil being relatively slowly degraded and sedimented, had effects on the plankton for at least as long as it remained visible in one form or another in these systems.

ACKNOWLEDGEMENTS

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TABLE 1

DESIGNATION OF PONDS

Pond Designation	Year	Type of Spill	Type of Oil	Amount of Oil
I	1974	Oil on ice	Norman Wells Crude	554 ℓ
II	1974	Oil under ice	Norman Wells Crude	90 ℓ
Control	1974			
III	1975	Oil under ice	Norman Wells Crude	45 ℓ
IV	1975	Oil under ice	Norman Wells Crude	90 ℓ
V	1975	Oil under ice	Pembina Crude	90 ℓ
Control	1975			

TABLE 2

ZOOPLANKTON IN PONDS DURING 1975 FIELD SEASON

	21/1	25/2	1/4	19/4	14/5	31/5	14/6	28/6	12/7	9/8	6/9
Rotifera											
Pond I	224		4	9							
Pond II	40	392	96	34				3			
Control	118	1152	118	50	1			2		9	4400
Oligochaeta											
Pond I	2		3	17							
Pond II	38		8				2			1	3
Control	12		1			1	1	1		1	
Cladocera											
Pond I	792		78	26							
Pond II	512	840	280	23			30	2	6	6	25
Control	232	112	116	22	10	105	46	49	2720	6080	2360
Calanoida											
Pond I	8										
Pond II	3										
Control						1			5	680	1080
Cyclopoida											
Pond I	3		1								
Pond II	24		4						1	1	2
Control	6	2	3		5	420	1	1	150	60	
Copepod nauplii											
Pond I	37		4	4							
Pond II	2	208	136	10	4			3		300	26
Control	6	128	29	65	10	1245	420	69	880	3760	4560

TABLE 3

WATER CHEMISTRY PARAMETERS (1974)

PARAMETER	SAMPLING DATES												
	21/1	26/2	1/4	19/4	14/5	31/5	14/6	28/6	12/7	26/7	9/8	23/8	6/9
Dissolved Oxygen (ppm)													
Control Pond	13.8	12.3	14.6	13.7	12.0	10.8	9.3	10.0	9.0	8.2	7.4	8.4	9.1
Pond I	13.0			9.6	9.6	3.6	8.4	8.4	9.4	7.0	5.4	4.2	5.7
Pond II	14.0	12.8	12.4	14.6	12.3	10.2	8.3	8.7	8.8	9.6	6.9	6.2	8.3
Alkalinity (ppm $CaCO_3$)													
Control Pond	(80)	(104)		18	15	14.5	14.2	7.0	15.5	13.5	16.5	11.0	
Pond I	(80)			7.0	9	11.0	4.5	1.0	4.5	1	1	1	
Pond II	(86)	(116)	61	23.5	16	14.5	13.8	7.5	4.5	11.0	11.5	7	
pH													
Control Pond	7.24			7.1		7.15	8.2	9.2	7.6	6.8	7.2	7.6	8.3
Pond I	7.19			7.0		6.65	6.35	6.1	6.5	4.9	4.9	5.0	5.1
Pond II	7.52			7.15		6.85	7.7	7.1	6.5	7.2	6.6	6.6	6.9

TABLE 4

ZOOPLANKTON IN PONDS DURING 1975 FIELD SEASON

	9/12/74	18/2/75	26/2/75	19/3/75	16/4/75	14/5/75	18/6/75	16/7/75	14/8/75	10/9/75	8/10/75	17/12/75
Rotifers												
Pond III	61	7316		3248	3200	4	80	3	1			
IV	141	106	247	73	21	1	3	4	3			1
V	1372	128	39	816	1		3					1
C	1336	3356	39	16	13888	512	208	4		16	24	5
Oligochaeta												
Pond III							4					
IV												2
V												
C									6	X		12
Cladocera												
Pond III	1	704		448	32	72	1424	436		3	2	
IV	4	8	5	4	4	9	60	83	1	3	3	9
V		256	1		4	3	60	5	1	640	3	X
C	64	256	11	5	1948	5120	1152	11	2	32		2
Copepod nauplii												
Pond III	3	11968		15104	2560	684	112	728	84	23		
IV	3	144		195	104	45	4	7	1	134	103	4
V			2	4644	20	13	4	2	1	12	103	9
C	X	11480	38	38	5920	35840	96	3	25	2656	1420	1
Calanoida												
Pond III	2											
IV	1											
V		16										
C							52					
Cyclopoida												
Pond III	3	3520		1408	1024	104	12		3			
IV	2	44	18	6	42	2		3	20	2		
V		672	8	448	9					2		
C	168	2944	18	25	3584	9984	176	1	11	288	44	2
Diptera												
Pond III									2	1	1	
IV							1	8	12			
V						5	1					2
C								1				

X = abundant; C = control.

TABLE 5

WATER CHEMISTRY PARAMETERS (1975 - 76)

SAMPLING DATES

PARAMETERS	9/12	12/2	19/2	26/2	5/3	19/3	2/4	16/4	30/4	14/5	4/6	18/6	2/7	16/7	30/7	13/8	27/8	10/9	24/9	8/10	22/10	19/11	17/12	11/2/76
Dissolved Oxygen (ppm)																								
Control	13.1	13.5	10.2	12.0	12.6	12.5	-	10.0	10.2	8.4	8.8	10.4	8.5	6.7	9.4	8.4	9.3	9.6	9.2	9.4	10.7	8.2	11.0	3.77
Pond III	13.1	13.6	12.3			13.2		9.8	10.1	7.4	7.4	8.4	6.5	5.2	8.4	7.9	9.0	9.2	9.6	10.4	11.1	8.9	10.8	6.6
Pond IV	13.1	13.6	13.6	12.5	14.0	13.0		9.4	9.6	7.5	7.0	8.6	6.2	4.2	8.0	7.0	7.4	8.7	8.6	9.3	10.3	9.7	10.5	5.1
Pond V	13.1	13.6	13.6	13.2	13.5	13.2		9.3	9.1	7.8	7.4	7.4	5.4	6.2	6.5	6.0	7.6	8.2	7.8	9.2	10.1	8.8	10.6	1.1
Alkalinity ($\sigma CaCO_3$) ppm																								
Control	8.0	11.3	11.0	12.1	10.0	4.5	12.5	6.5	9.3	12.7	12.8	9.2	6.7	12.5	13.9	14.7	15.2	10.3	9.8	11.3			10.9	13.0
Pond III	11.3	18.0	19.0			14.4	17.8	4.0	10.6	12.4	12.6	8.5	12.3	15.0	7.0	23.8	21.5	14.5	14.9	12	10.1	4.0	1.0	0.7
Pond IV	9.1	15.5	16.7	11.1	15.6	7.3	24.0	10.0	13.6	16.1	15.5	11.3	13.2	13.3	7.0	27.4	13.8	6.1	6.7	15.9	.01		5.2	10.1
Pond V	10.6	11.1	16.2	8.5	14.8	8.0	14.8	11.5	5.0	9.4	8.8	5.2	11.5	3.8	5.5	6.4	15.8	1.0	0.1	5.4	.01			7.4
pH																								
Control	6.3	6.5	6.4	7.1	6.5	6.0	6.5	6.2	6.5	6.6	7.5	6.6	6.9	7.5	7.8	6.7	6.8	5.9	7.1	6.8	5.9		10.9	6.2
Pond III	6.9	6.6	6.7			6.8	6.6	5.8	6.5	6.8	7.5	6.4	7.4	9.0	7.2	7.3	6.6	5.7	7.1	6.7	5.8		6.4	6.5
Pond IV	6.5	6.5	6.6	7.1	6.8	6.2	6.8	6.4	6.6	6.8	7.7	6.7	7.5	7.4	7.4	6.6	6.6	6.2	6.7	6.7	5.8		6.0	5.8
Pond V	6.9	6.5	6.6	6.7	6.8	6.7	6.5	6.5	6.4	6.4	7.3	5.9	9.2	7.0	7.3	6.6	7.1	5.0	6.2	6.7			5.3	5.3

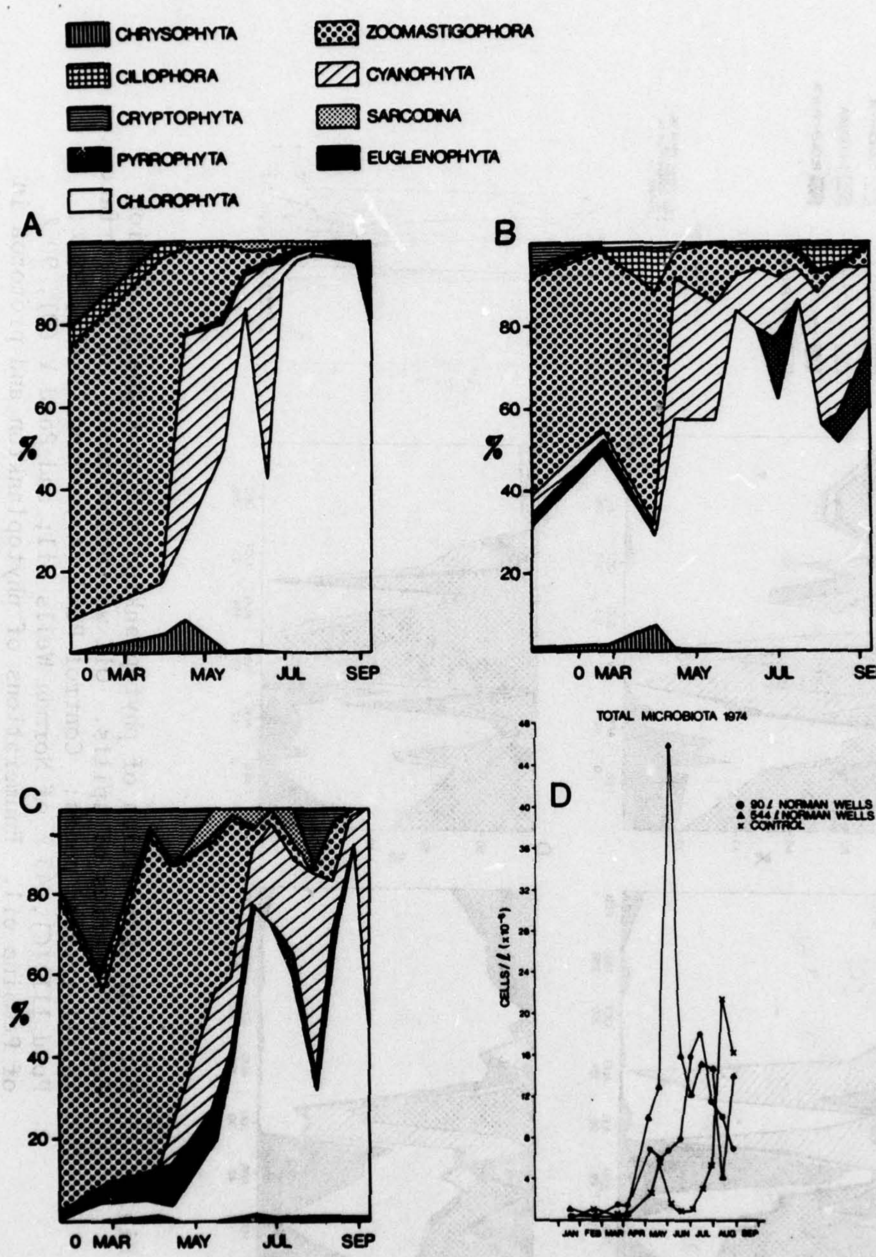

Fig. 1 Per cent composition of phytoplankton and protozoa population for 1974 series of spills. Pond I (A), 554ℓ Norman Wells oil added on the ice; Pond II (B), 90 ℓ added under the ice; Control Pond (C). Enumeration of phytoplankton and protozoa in the ponds are shown (D).

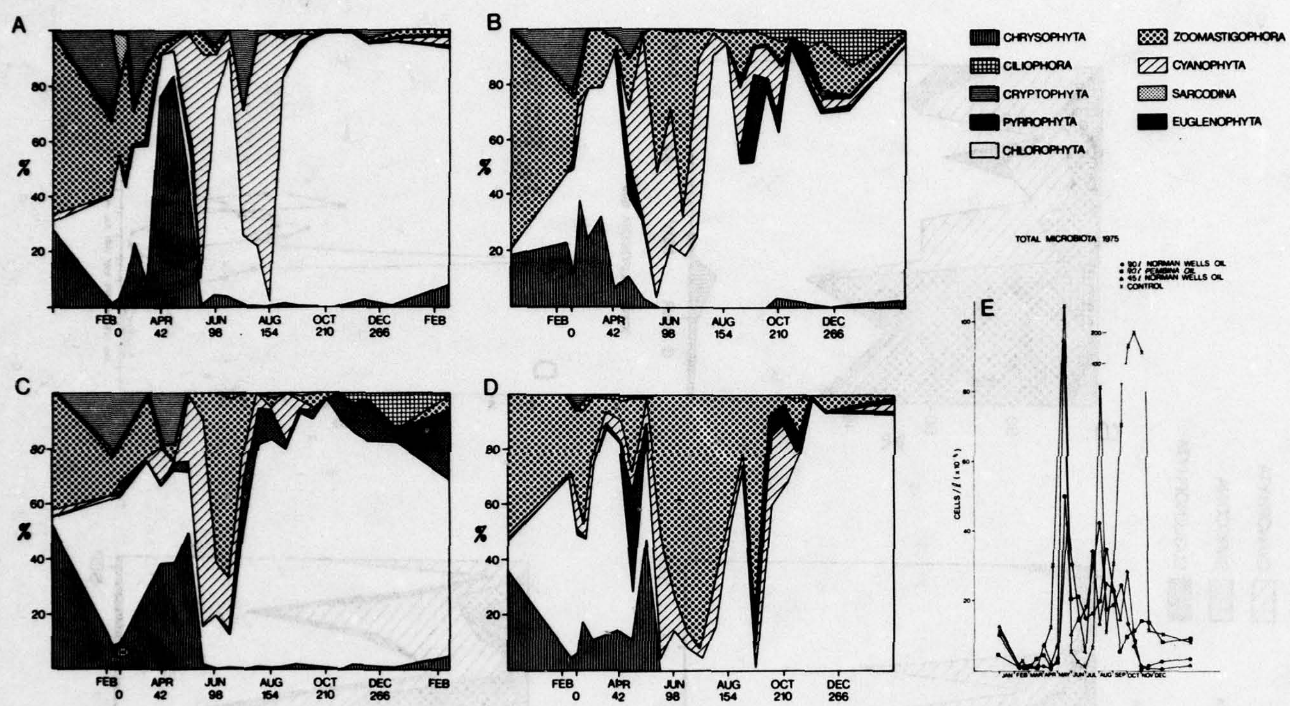

Fig. 2 Per cent composition of phytoplankton and protozoa population for 1975 series of spills. Oil was added under the ice surface in all treated ponds: Control Pond (A); Pond IV (B), 90 ℓ; Pond III (C), 45 ℓ of Norman Wells oil; and Pond V (D), 90 ℓ of Pembina oil. Enumerations of phytoplankton and protozoa in the ponds are shown (E).

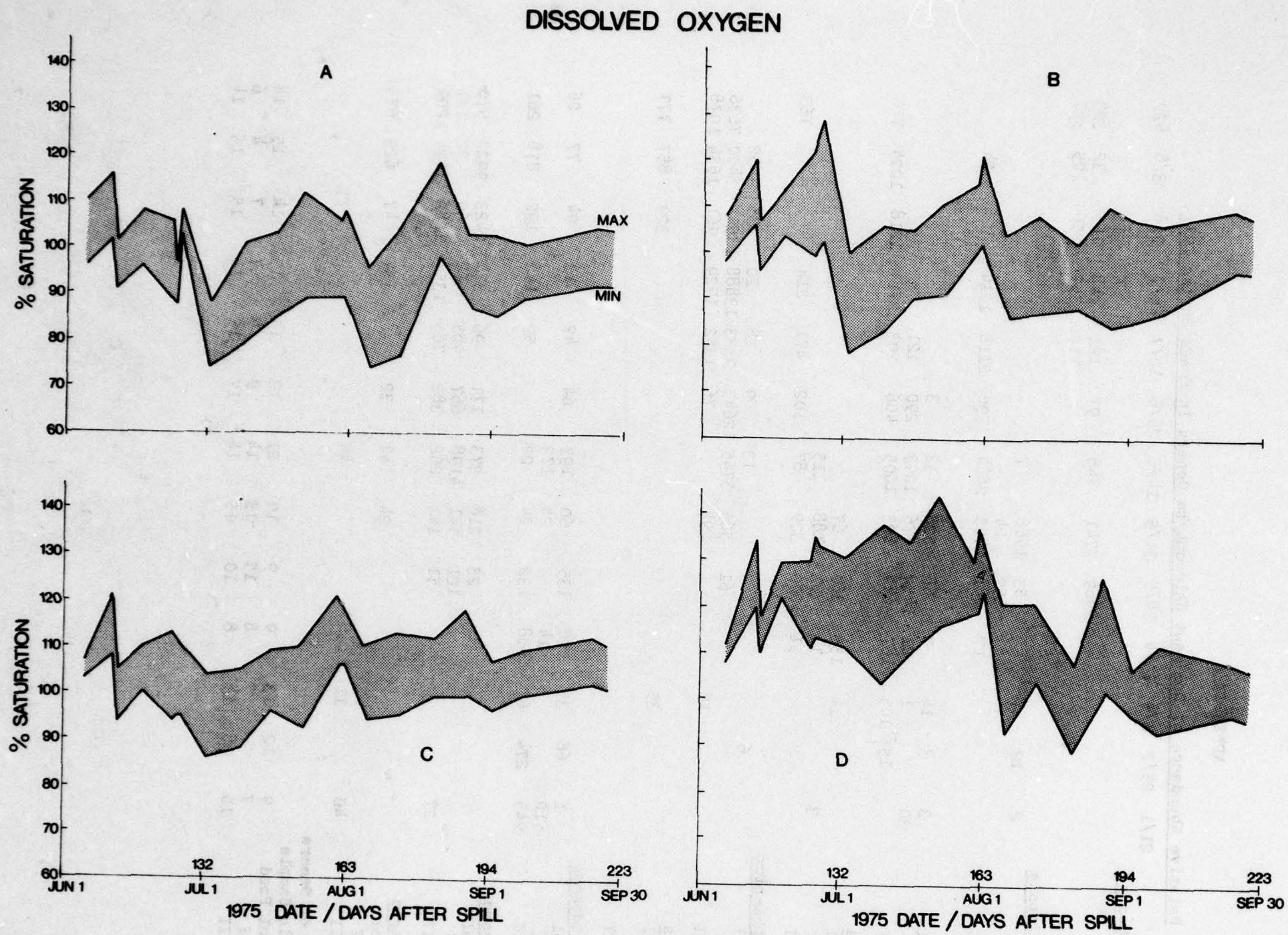

Fig. 3 Minimum and maximum diurnal dissolved oxygen concentrations in the ponds during the summer of 1975: Pond V (A), Pond IV (B), Pond III (C), and the Control Pond (D). Minimum values occurred just past sunrise after about 12 hours respiration during the night; maximum values occurred near sunset after the day's photosynthetic O_2 evolution. Each inflection point represents a measurement.

APPENDIX A

Relative Abundance of Dominant Chlorophyta Genera In Ponds During 1974

	21/1	25/2	1/4	19/4	14/5	31/5	14/6	28/6	12/7	26/7	9/8	23/8	6/9
Chlamydomonus													
Control							7		6	6	12		
Pond I					2969	7741	748	97	121	48	165	32	303
Pond II									117	357	256	195	327
Sphaerellopsis													
Control	2	12	7		53	1968	7						
Pond I					152	24							
Pond II				17	881	2705	2884	790	2118	1214		24	
Gonium													
Control	3	3	14	7	68	528	33	3					
Pond I	30		1	21	1454	776	1093	290	121				
Pond II		15	105	167	642	823	1005	406	203	2714	1218	1024	710
Eudorina													
Control			14	158	360	67							
Pond I	3			11	91	188	115						
Pond II				51	1000	329	87	102	471	214			163
Dictyosphaerium													
Control		6					13	9	18	20	35	52	
Pond I					61	565	3795	12645	9333	13888	13554	3400	7636
Pond II			18			94		76	1352	1929	961	1634	1078
Oöcystis													
Control			35								329	857	777
Pond I													
Pond II													
Ankistrodesmus													
Control	1	66	35	28	135	60	193	64	42	13	94	77	26
Pond I	10		5	14		24	173						
Pond II	945	274	67	388	132	24	22		59	142	192	878	261
Scenedesmus													
Control					23	216	273	177	96	374	2423	9922	570
Pond I					121	541	4198	667	485	64	60	32	121
Pond II	27				51	141	262	382	765	1357	1282	1024	1209
Starastrum													
Control						24	47	32		34	47	623	673
Pond I													
Pond II	40		11				44						
Number of Genera Found in Sample													
Control Pond	9	12	13	9	9	10	21	13	14	15	14	15	14
Pond I	7		7	8	15	13	14	9	4	7	7	4	6
Pond II	10	8	11	8	10	15	14	17	15	14	15	15	14

APPENDIX B

Relative Abundance of Dominant Chlorophyta Genera Found in Ponds During 1975

	12/2	18/2	24/2	5/3	19/3	2/4	16/4	30/4	14/5	4/6	18/6	2/7	16/7	30/7	13/8	27/8	10/9	24/9	8/10	22/10	19/11	17/12
Chlamydemonus																						
Control	32	97	5	15	4	12	20	34	40	104		5					15	35	85	22	3	
Pond III	46	62			5	37	6		20		33						25	245	308	12	5	5
Pond IV	21	28	11	54	8	5	4	23	91	75	75		40	160	320			32	110			
Pond V	50	31		11	10	1	3		33	54				67				60		44	20	52
Gonium																						
Control		21	8	27	10	58	40	134	16												10	12
Pond III					34	90	42	77								52	20	60	10	8		
Pond IV			9	36	22	96	6	67					46	28								10
Pond V				50	8	20	4	62												7	10	35
Eudorina																						
Control		2																				
Pond III		3								26											8	2
Pond IV					6			40	158		14		188									
Pond V		8			232	164															120	
Dictyosphaerium																						
Control																			25	185	25	
Pond III																	130	80		8	4	
Pond IV																	400	128	370	65	3	
Pond V														22	13		70	84	480	1237	1120	613
Ankistrodesmus																						
Control					4	3	5	60	112	4			12	21	91	30	2282	13080	18000	13340	880	4
Pond III						10		8	62		25		675	406	375	170	315	1585	465	52	54	14
Pond IV																11	112	32	30	8	24	14
Pond V											7	5				6	16	28	15	17	10	3
Kirchneriella																						
Control											7	3			196	1308						
Pond III												55	5	58	306	588						
Pond IV												6	1880	3370	166	673						
Pond V											9											
Scenedesmus																						
Control						4		24	116	34	6	9	42	36	317	308	116	335	830	288	5	1
Pond III						10		8	62			25	540	304	466	138	215	310	52	54	4	6
Pond IV								8	27	12	8	110	84	30	120	24	44	132			12	16
Pond V								7	51	41	36	16	17	186	1061	8	48	112	140	7		5

EFFECTS OF SPILLS ON BENTHIC ORGANISMS

Chairman: JACK ANDERSON
Battelle Pacific NW Laboratories

THE INFAUNAL BENTHOS OF PETROLEUM-CONTAMINATED SEDIMENTS: STUDY OF A COMMUNITY AT A NATURAL OIL SEEP

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ABSTRACT

A diverse Nothria-Tellina assemblage exists in sediments containing 3,300 to 10,200 ppm of crude oil. Community changes over a two-year period are compared with those in a nearby non-seepage area. The faunas are similar, except for the high abundance of oligochaetes in the seep sediments. Several measures of community structure (diversity) indicate relative constancy between stations and seasonally. Several measures indicate relatively less community stability at the seep station. Sediment ATP concentrations were 809 mg ml^{-1} in areas of active seepage but only 146 to 402 mg ml^{-1} in other areas, which supports our earlier hypothesis of trophic enrichment. The water-soluble fraction of Prudhoe Bay crude oil is slightly more toxic to the larvae of the starfish *Patiria miniata* than is the seep oil. The described chemical differences between these oils are related to possible biological effects.

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INTRODUCTION

We are studying the effects of a submarine oil seep on an ecosystem in the shallow coastal waters off Southern California. The oil-contaminated sediments of this Isla Vista seep provide a natural laboratory for our studies on chronic hydrocarbon effects. These studies complement other ecosystem-effects studies such as CEPEX (Controlled Ecosystem Pollution Experiment), done with captive planktonic communities in Puget Sound (Lee et al 1977) and MERL (Marine Ecosystem Pollution Experiment), which used transplanted sediments from neighboring Narragansett Bay in flow-through microscosms (Kerr 1977). While these latter experimental approaches retain control of dosage, we have been making measurements of a natural system and formulating testable hypotheses on the effects of petroleum.

The initial results of our study (Spies and Davis 1978) indicate that the infaunal benthos of the Isla Vista oil seep is diverse and representative of the *Nothria-Tellina* assemblage, which is a broad-scale feature of the Southern California mainland shelf (Barnard and Hartman 1959). The infauna of the seep area is denser than that of a comparison area, but other community parameters such as dominance-diversity values and polychaete biomass are similar. Dense populations of oligochaetes at the seep suggest an advantage to deposit feeders. We hypothesized that enrichment of the seep community resulted from the added production of hydrocarbon-degrading and sulfide-oxidizing microbes. Also, based on these results and determinations of hydrocarbon body burdens by Straughan (1976), we suggested that either seep organisms are biochemically adapted to petroleum hydrocarbons or the seep environment is not toxic to the organisms.

We report here on faunal changes over a 2-year period and interpret these in terms of functional community differences resulting from the fresh seep oil in sediments. We also present further evidence of trophic enrichment and a preliminary charcterization of the seep oil. Further, we compare the toxicities of the seep oil and of Prudhoe Bay crude oil to the embryos of the starfish *Patiria miniata*.

MATERIALS AND METHODS

The Seep Environment and Station Location

The Isla Vista seep is a major contributor to the estimated 50 to 70 bbl d^{-1} of oil seeping into the Santa Barbara Channel from the Coal Oil Point area (Allen et al., 1970). The area of this particular seep is about 1000 m^2. We have located our sampling station on the seaward edge of the seep on a fine sand bottom. A nearby comparison station without fresh seepage was selected (Fig.1). Further details of the seep environment are given elsewhere (Spies and Davis, 1978).

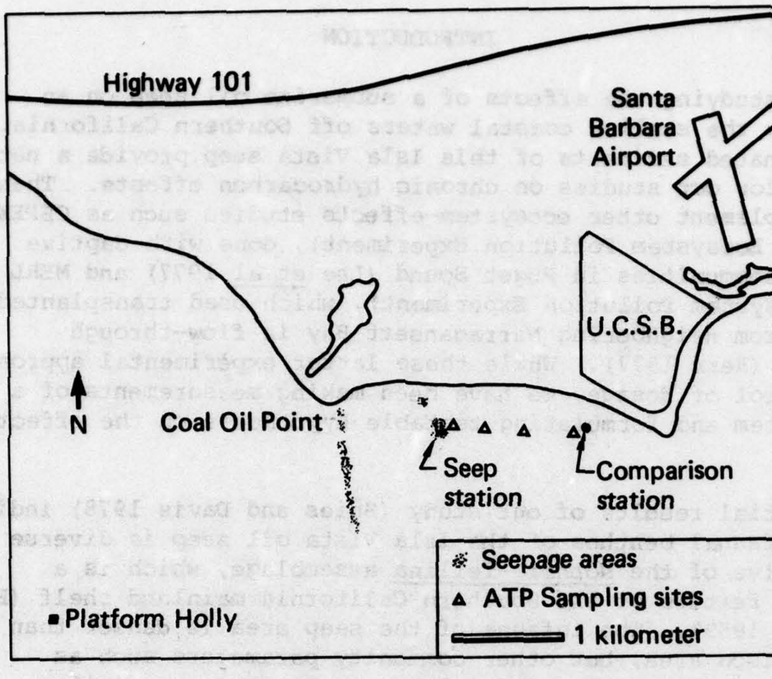

Fig. 1. Map of study area.

Faunal Sampling

Each station is 50 m^2 and divided into 200 quadrates. Approximately every 8 weeks, ten 0.019-m^2-core samples were collected at each station. These were sieved on a 0.5-mm screen, preserved, sorted, and the component populations enumerated by the usual methods. Data relating to adequacy of sampling for horizontal patchiness and vertical distribution are presented elsewhere (Spies and Davis, 1978).

Chemical Sampling and Analyses

Seep oil was collected in inverted jars from an area of intense seepage close to the faunal sampling station. Prudhoe Bay crude oil was provided by Dr. Jack Anderson of Battelle's Sequim Marine Laboratory.

Oil samples were dissolved in carbon disulfide (40 μg/μl) and analyzed by splitless, glass-capillary, gas chromatography (GC) on a Varian* model 3700 gas chromatograph equipped with a flame, ionization detector and a 30-m (0.3 mm i.d.) WCOT SP2100 column. The column temperature was increased from 35 to 225 ^{o}C at 3 ^{o}C/min and held at the final temperature for 30 min. The column flow rate was 1.6 ml/min.

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*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

Low-molecular-weight components of the seep oil were determined by analysis of a 200°C distillate by combined GC and mass spectrometry (MS) with a Hewlett-Packard model 5985 GC-MS-Data System. The GC conditions are described above. Individual compounds were identified by comparing their retention times and mass spectra to those of known compounds.

Semivolatile hydrocarbons were determined on 65-g subsamples obtained from homogenized 20-cm-deep cores. The samples were acidified, water washed, and lyophilized. Total hydrocarbons were extracted with 3:1 methanol:toluene in a Soxhlet apparatus for 48 h. The total extract was concentrated on a rotary evaporator and then fractionated by chromatography on a silica gel (1.5% deactivated) column into hexane, toluene, and methanol fractions (1 column volume each). The hexane fraction was run through an activated-copper column to remove elemental sulfur. The solute weight of each fraction was determined by evaporation of an aliquot on a microbalance pan.

Water-soluble fractions were prepared by carefully layering 150 ml of oil on 3 liters of filtered seawater, using a 1μ, Filtrex cotton-wound cartridge filter, and then slowly stirring for 48 hr at 20°C in a closed container.

Toxicity Experiments

A simple embryological bioassay, using the common Pacific subtidal starfish *Patiria miniata*, has been developed. Starfish were collected near San Luis Obispo and allowed to acclimate to our seawater system for 2 days. After sitting in air for 2 to 3 hours, ripe animals spawned and the gametes were collected. Sperm was diluted 1:2000 in seawater to prevent polysperm and maximize fertilization success. Eggs were fertilized in 100, 75, 50, 25 and 10% solutions of the water-soluble fractions.

Two controls were also used. Eggs were gently washed and placed in fresh solutions of the water-soluble fractions after a 20-min exposure to sperm. A 450-ml beaker was used as the test chamber, and eggs were suspended on a nytex screen in the beaker. The assay was carried out for 48 h at 15°C. Embryos were fixed in 10% fomalin and later measured by using an ocular micrometer on the microscope.

Adenosine Triphosphate (ATP) Determinations

Triplicate determinations of ATP (Karl and LaRoche, 1975) were made on samples from the surface of the sediment at several stations located between the Isla Vista seep and the Mohawk reef in the Santa Barbara channel (Fig. 1). All stations were 15 to 16 m deep and on fine sandy bottom. Besides the sites shown in Fig. 1, samples were taken at the regular seep sampling station, also at an area of intense seapage, and at an area near Mohawk Reef.

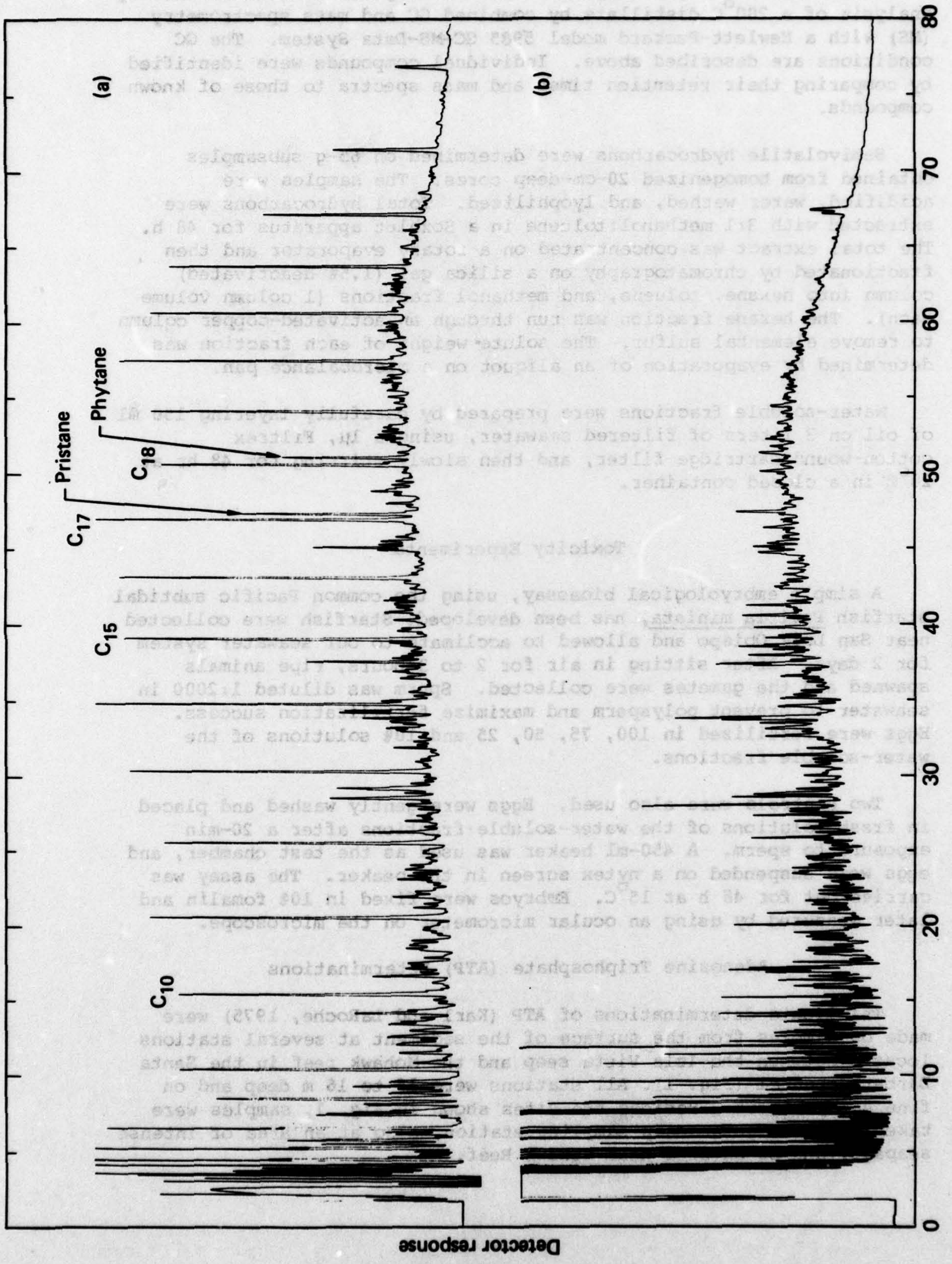

Fig. 2. Chromatograms of crude oils: (a) Prudhoe Bay and (b) Isla Vista seep.

RESULTS

Oil Characteristics

The hydrocarbon distribution of Prudhoe Bay crude oil is typical in general of many crude oils. The composition (Fig.2a) is dominated by the n-alkanes, the major hydrocarbons being n-pentadecane and n-heptadecane. The odd-numbered-carbon n-alkanes predominate slightly over the even-numbered ones (Carbon Preference Index, C_{14-23} = 1.01). Pristane (2,6,10,14-tetramethylpentadecane) and phytane (2,6,10,14-tetramethylhexadecane) are also major components, representing 59% and 60% of the n-heptadecane and n-octadecane, respectively.

By contrast, the Isla Vista Seep oil contains an unusually high proportion of low-molecular-weight hydrocarbons (Fig. 2b) and an unresolved complex mixture of branched, naphthenic and aromatic hydrocarbons (the large brood hump on the chromatogram). Normal hydrocarbons, and pristane and phytane are not major components, although their presence has been demonstrated and described by Reed and Kaplan (1977). Over 60 peaks are resolved by GC before the boiling point of decane (retention time 15.5 min) is reached (Fig. 2b). Figure 3 presents the total-ion chromatogram of the low-molecular-weight components of this oil. The major components are branched alkanes from C_5H_{12} to $C_{10}H_{22}$, substituted cyclopentane and cyclohexane isomers, and C_1- to C_4-substituted benzenes. Normal alkanes are only minor components, and benzene is not detected.

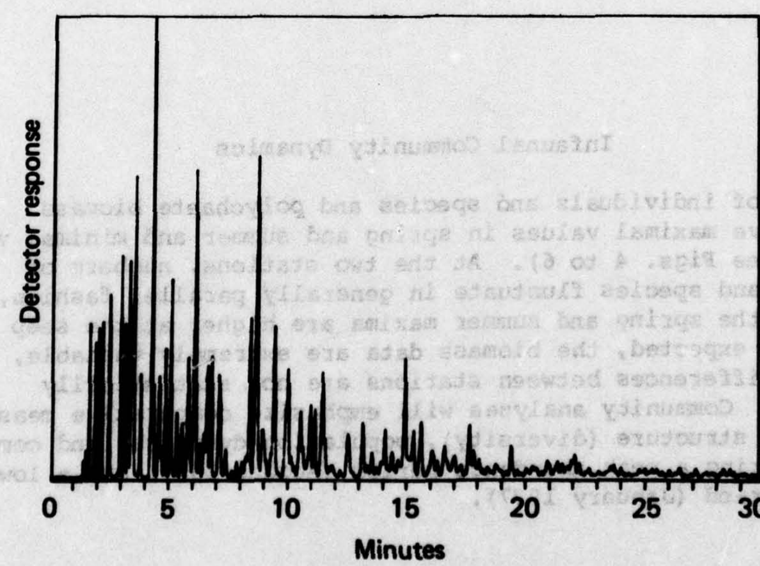

Fig. 3. Total-ion chromatogram of a 200°C distillate of Isla Vista seep oil.

Sediment Hydrocarbons

Marked differences in sediment hydrocarbons are observed between the seep and comparison areas. In Table 1, the data from two sets of samples, collected in January and October 1977, are compared. Differences in total hydrocarbon are observed for the two sampling times. Sediment composition is strongly affected by seasonal currents and storms. The temporal variations in hydrocarbon content may be the result of mixing and dilution by fresh sediments. Even so, the total hydrocarbon content of the seep area is 2.7-times (January) to 4.8-times (October) higher than that of the comparison area. Moreover, most of this difference is due to much higher contents of the hexane and toluene fractions at the seep area. The hexane fraction is 6.6-times (January) to 18.4-times (October) more concentrated in the seep area. From these data, we conclude that the seep-area sediments contain a high proportion of fresh seep oil while the comparison-area sediments mainly contain weathered seep oil and asphaltenes.

Table 1. Sediment hydrocarbons.

	Relative fraction weight			Total weight
Station date	Hexane	Toluene	Methanol	(g/kg dry sediment)
Seep 1/77	0.15	0.35	0.50	3.39
Seep, 10/77	0.23	0.48	0.29	10.19
Comparison, 1/77	0.06	0.27	0.67	1.28
Comparison, 10/77	0.06	0.09	0.85	2.11

Infaunal Community Dynamics

Numbers of individuals and species and polychaete biomass generally have maximal values in spring and summer and minimal values in winter (See Figs. 4 to 6). At the two stations, numbers of individuals and species fluctuate in generally parallel fashion, except that the spring and summer maxima are higher at the seep station. As expected, the biomass data are extremely variable, therefore, differences between stations are not statistically significant. Community analyses will emphasize comparative measures of community structure (diversity), population dynamics, and community stability during a peak abundance period (August 1977) and a low abundance period (January 1977).

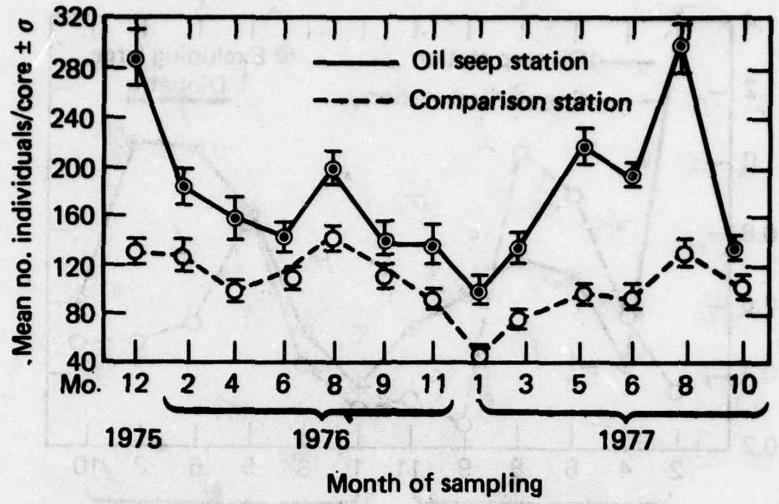

Fig. 4. Variations in numbers of organisms in samples.

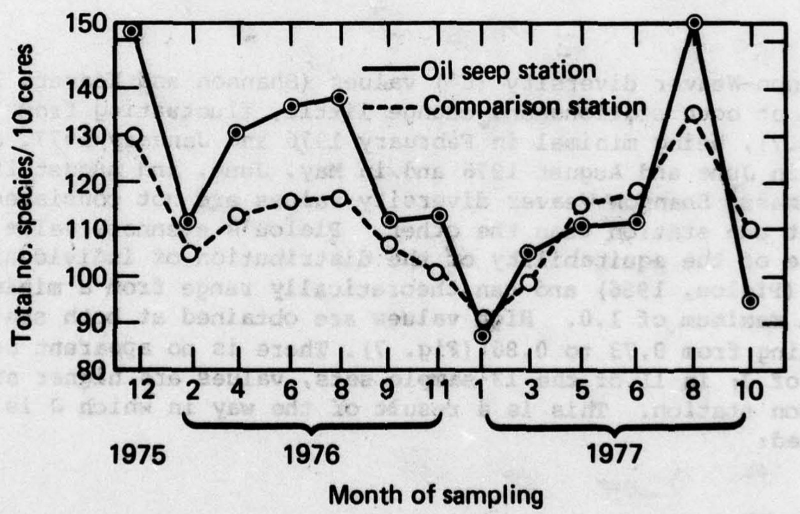

Fig. 5. Fluctuations in numbers of species in samples.

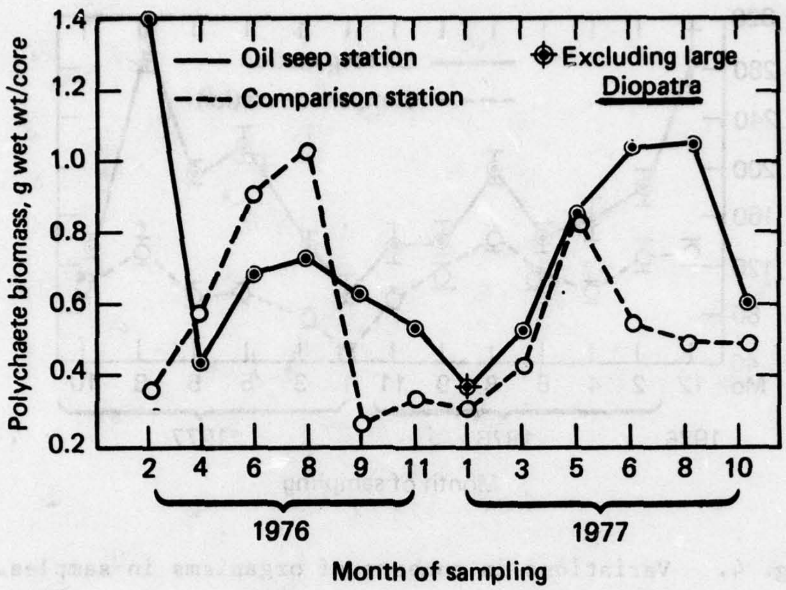

Fig. 6. Fluctuations in polychaete biomass in samples.

Shannon-Weaver diversity (H') values (Shannon and Weaver, 1963) are high at both stations and change little, fluctuating from 3.5 to 4.1 (Fig.7), being minimal in February 1976 and January 1977, and maximal in June and August 1976 and in May, June, and August 1977. As with biomass, Shannon-Weaver diversity values are not consistently higher at one station than the other. Pielou's evenness value (J) is a measure of the equitability of the distribution of individuals among species (Pielou, 1966) and can theoretically range from a minimum of 0.0 to a maximum of 1.0. High values are obtained at both stations, fluctuating from 0.73 to 0.86 (Fig. 7). There is no apparent seasonal pattern of J; in 11 of the 13 sample sets, values are higher at the comparison station. This is a result of the way in which J is calculated:

$$J = \frac{H'}{H'_{max}} = \frac{H'}{\log_2 s}$$

Because of the smaller number of species (s) at the comparison area, for most sampling periods, J has a higher value for equivalent values of H'.

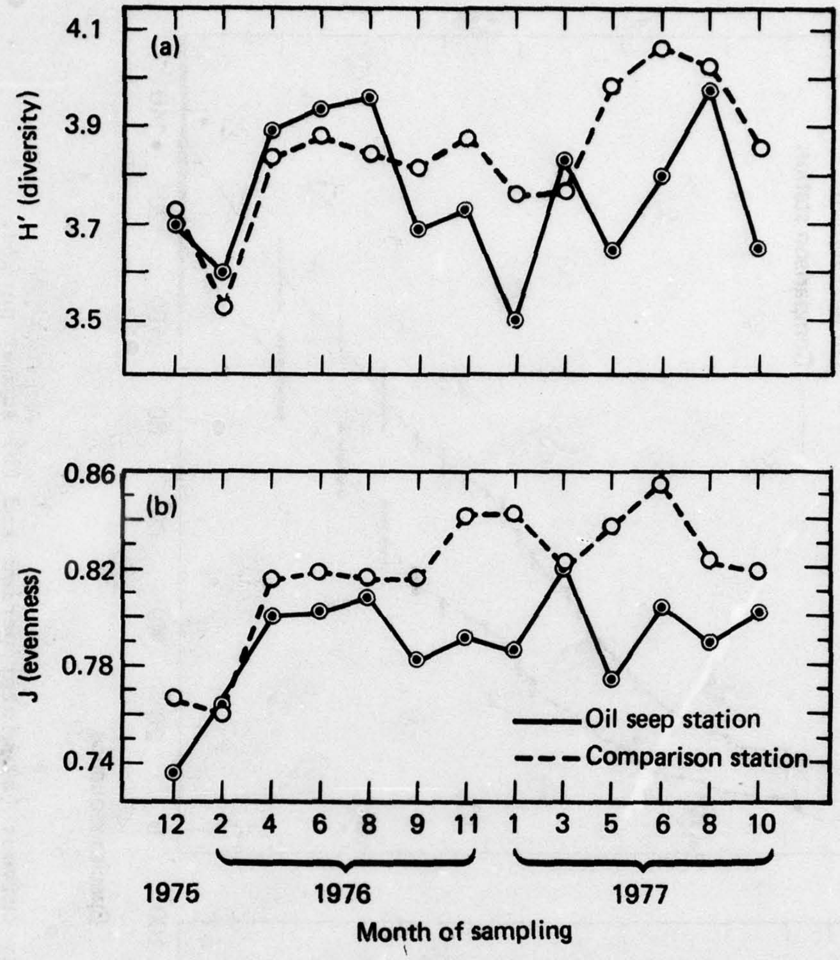

Fig. 7. Measures of diversity in samples.

Because a single index of diversity such as H' can be ambiguous when interpreting community structure and can be insensitive to changes in proportions of rare species, we also constructed dominance-diversity curves. For the January and August 1977 sample sets, the general shape of the curves were similar; their shallow slopes reflecting the large numbers of rare species (Fig.8).The curves for August 1977 were displaced considerably to the right because of higher densities.

To compare the shapes of curves we used the methods adopted by Watling (1975). The curve parameters, inclusive graphic skewness

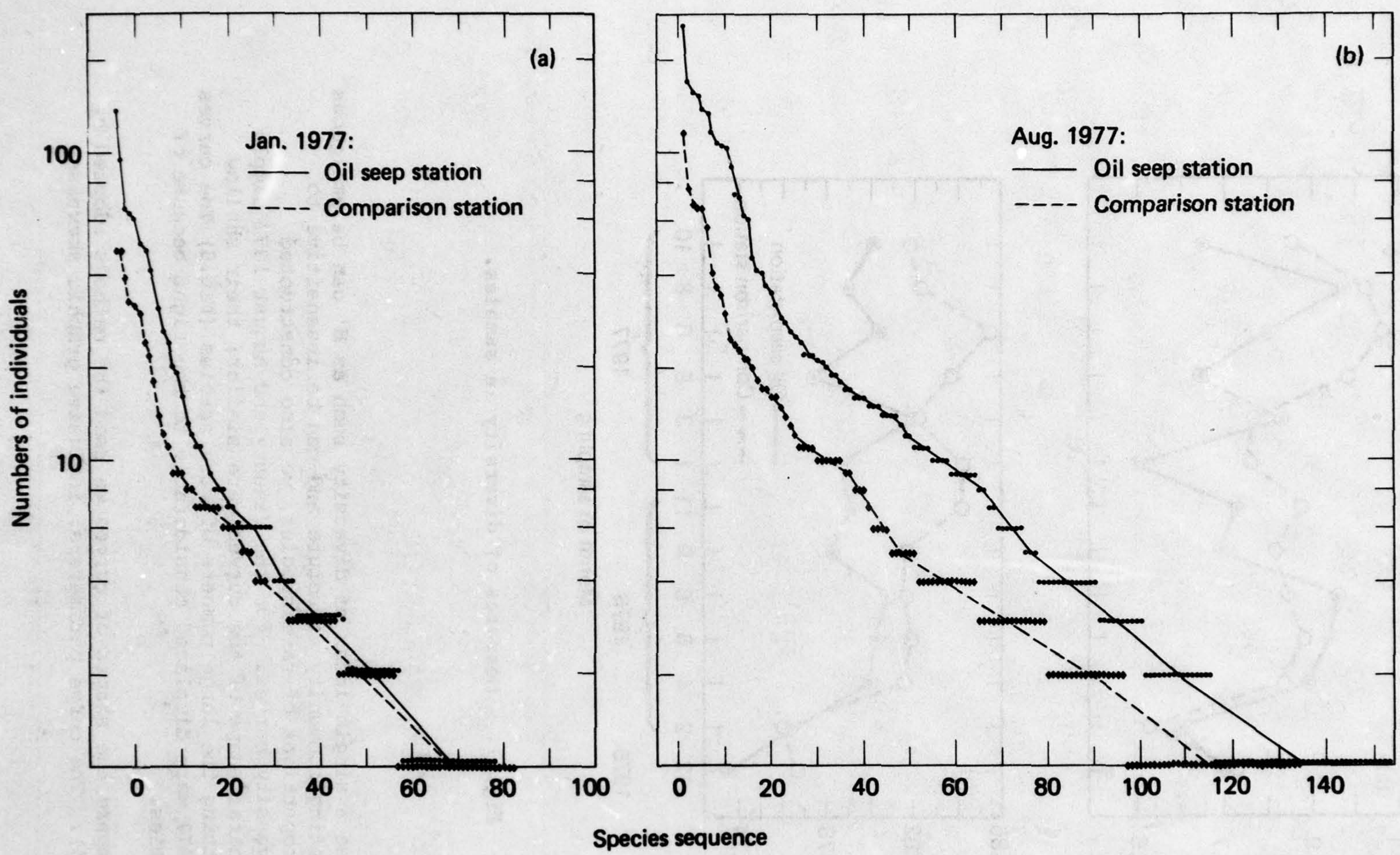

Fig. 8. Dominance-diversity curves: (a) winter period and (b) summer period.

(SK_I) and graphic kurtosis (K_G) were computed (Folk, 1968) from cumulative curves of percent abundance of individuals as a function of species sequence. Results are given in Table 2. The theoretical limits of SK_I are +1.0 to -1.0: values of 0.0 are from symmetrical distributions. Our values, 0.67 to 0.69, indicate distributions strongly skewed toward rare species. The minimum theoretical limit of K_G is 0.41, values from 1.1 to 1.4 are leptokuric. For the two stations, the close similarity of SK_I and K_G values from winter and summer periods, considered together with the small fluctuating values for H' and J, indicates a remarkable constancy of community structure. This constancy persists despite consistent density differences between stations and fluctuations of individuals from 5,210 to 15,400 m^{-2} at the seep station and 3,000 to 7,315 m^{-2} at the comparison station.

Table 2. Inclusive graphic skewness (SK_I) and graphic kurtosis (K_G) of dominance-diversity curves, January and August 1977.

Date	Seep station		Comparison station	
	SK_I	K_G	SK_I	K_G
1/77	0.68	1.4	0.67	1.1
8/77	0.68	1.3	0.69	1.2

If community structures are similar, how similar are the faunas at the two stations? This question can be answered by comparing the species present and their relative contributions to the fauna of each station at different seasons. Before making these comparisons, it should be restated that the faunas of both stations are generally representative of the Nothria-Tellina assemblage, with the exception of the high density of oligochaetes at the seep station. The most abundant species are listed in Table 3. Of a total of 319 species, 71% were found at both stations; of the remaining 29%, nearly all in any sample set were represented by <3 individuals. Because of sampling artifact resulting from the many rare species present at each station, we can attach no significance to the dissimilarity of the two lists. We also determined the extent of the similarities in rank order of common species, those occurring in >50% of the cores, at the two stations. Significant correlation (Spearman's rho = 0.605, p >0.025) in rank orders was found in January 1977 and highly significant correlation (Spearman's rho = 0.673, p >0.001) was found in August 1977. Another indication of faunal similarity is that species occurring at both stations accounted for 86% and 93% of individuals in January and in August, respectively, of 1977.

Table 3. Ten most abundant taxa from all sampling periods.

Taxa	Density/core
Seep Station:	
Oligochaetes	13.8 ± 7.8
Tellina modesta	12.9 ± 7.2
Mediomastus californiensis	12.0 ± 7.7
Euphilomedes sp.	9.6 ± 2.2
Prinospio pygmaea	9.2 ± 4.3
Tharyx nr tesselata	8.7 ± 4.9
Nepthys caecoides	5.1 ± 3.6
Tellina nuculoides	4.9 ± 2.6
Comparison Station:	
Nematodes	9.1 ± 5.5
Euphilomedes sp.	6.8 ± 1.7
Prinospio pygmaea	6.4 ± 4.7
Tellina modesta	4.1 ± 2.3
Chaetozone setosa	4.0 ± 3.4
Mediomastus acutus	3.6 ± 1.5
Paraphoxus abronius	3.6 ± 2.3
Mediomastus californiensis	2.9 ± 2.1
? *Lytechinus pictus*	2.7 ± 4.4
Nereis procera	2.2 ± 2.7

Population Dynamics

The strong similarities in community structure (diversity) and faunas prompted us to examine component populations for differences between stations. A number of patterns can be recognized, and three representative examples are shown in Fig. 9. First, as typified by the polychaete *Chaetozone setosa* in (a), a majority of species fluctuate in general concordance with community density. Second, a smaller number of species, such as the bivalve *Parvilucina approximata* in (b), tend to have peak abundances in autumn, shortly after the seasonal community peak. Third, some species show either no apparent pattern or a single peak abundance, such as the small anemones of *Edwardsia* sp. in (c). As might be predicted, most populations are consistently denser at the seep station and show large peak abundances in spring and summer. The relatively larger fluctuations in many populations at the seep station and the fact that some population fluctuations are out of phase with community density suggests that community stability could differ at the two stations.

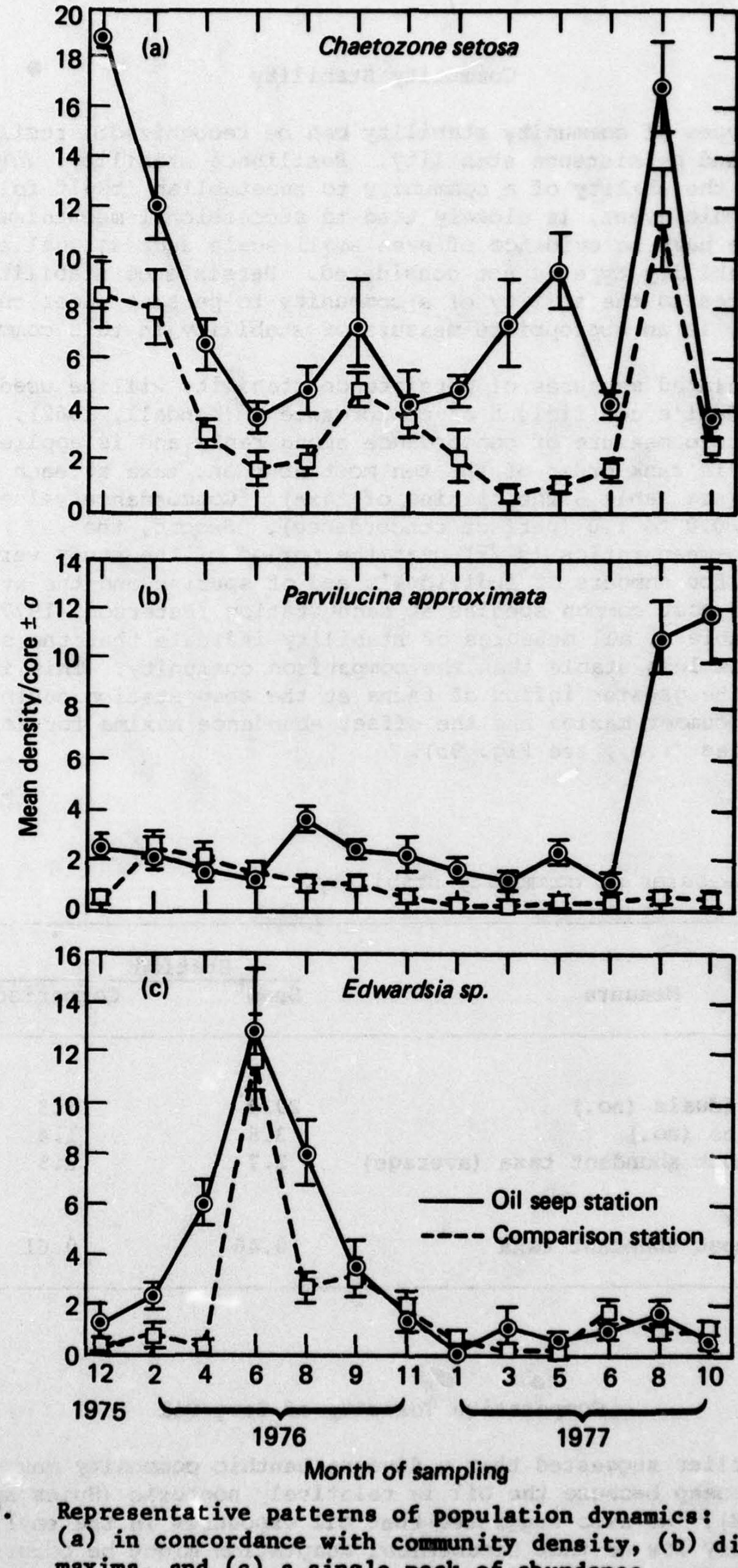

Fig. 9. Representative patterns of population dynamics: (a) in concordance with community density, (b) displaced maxima, and (c) a single peak of abundance.

Community Stability

Two types of community stability can be recognized: resilience stability and persistence stability. Resilience stability, which relates to the ability of a community to reestablish itself following a catastrophic event, is closely tied to successional mechanisms. However, we have no evidence of even small-scale successional events, so this stability type is not considered. Persistence stability, which relates to the ability of a community to persist under changing conditions, is an appropriate measure of stability in this community.

Two related measures of persistence stability will be used. The first, Kendall's coefficient of concordance W (Kendall, 1962), is a non-parametric measure of concordance among ranks and is applied here to changes in rank order of the ten most abundant taxa at each station with time (see Table 3 for listing of taxa). Concordance values can range from 0.0 to 1.0 (perfect concordance). Second, the variance-to-mean ratios ($s^2/\bar{x}$) over the period of the study were calculated for numbers of individuals and of species and the average for the ten most common species at each station (Peterson, 1977). As shown in Table 4, all measures of stability indicate that the seep community is less stable than the comparison community. This is the result of the greater influx of fauna at the seep station during the spring and summer maxima and the offset abundance maxima for some other species (i.e., see Fig. 9b).

Table 4. Measures of community stability.

Measure	Station: Seep	Station: Comparison
$s^2/\bar{x}$:		
Individuals (no.)	20.9	5.3
Species (no.)	3.6	1.4
Ten most abundant taxa (average)	2.7	2.5
Kendall's W:		
Ten most abundant taxa	0.46	0.61

Comparative Toxicity of Seep Oil

We earlier suggested that a diverse benthic community may develop in the oil seep because the oil is relatively nontoxic (Spies and Davis, 1978). We also suggested that oil exposures in the environment might be very low or that biochemical adaptation might be occurring. To test the first possibility, we compared the toxicity of the seep

oil to that of Prudhoe Bay crude oil. Considerable information is now available on the toxicity of Prudhoe Bay oil (Rice et al., 1976; Shaw et al., 1977; and Taylor and Karinen, 1977). This oil is being shipped in large quantities through the Santa Barbara Channel, so it is also a potential pollutant. Results of embryo toxicity tests (see Materials and Methods) are given in Figure 10. Both oils have a marked effect on the growth of embryos; the effects of Prudhoe Bay crude oil are more severe. Although the error bars overlap at all concentrations of water-soluble fractions, the different slopes of the curves indicate some toxicity differences. The dashed error bars indicate a more variable effect of Prudhoe Bay crude oil on the embryo population.

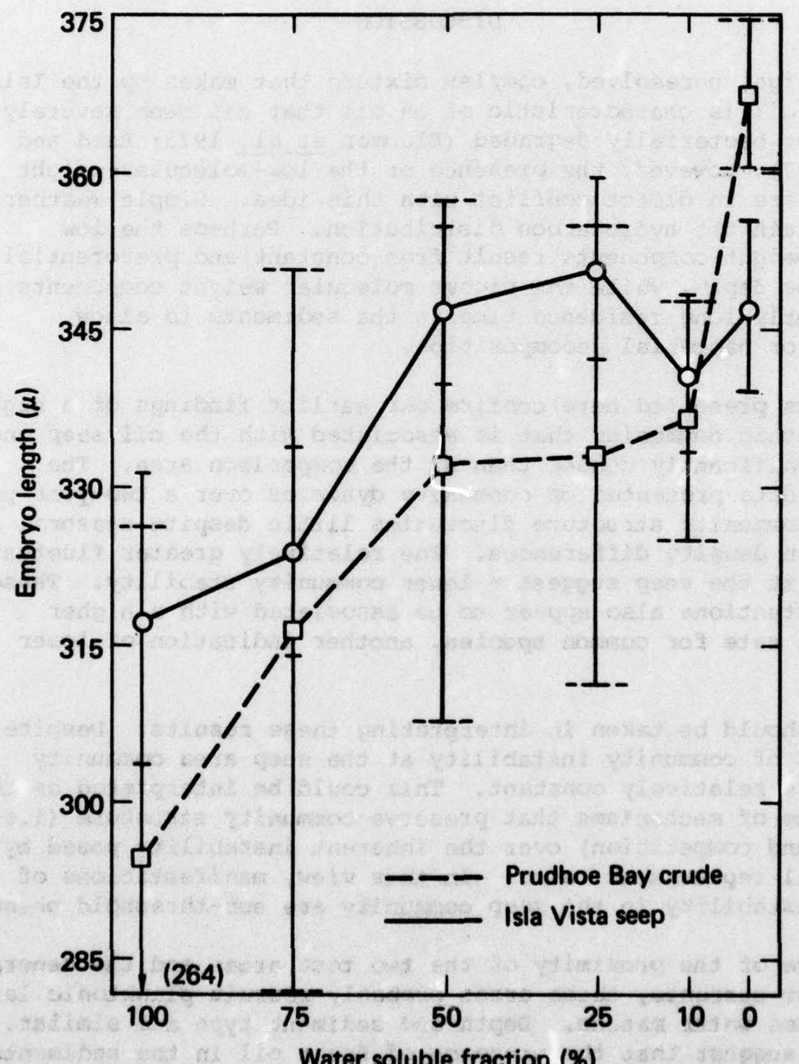

Fig. 10. Effect of the water-soluble fractions of oils on growth of Patiria miniata embryos (static exposure for 48 hours).

Community Enrichment

We have also hypothesized that the relatively dense benthic community in the seep area was trophically supported by populations of hydrocarbon-degrading and sulfide-oxidizing microbes. To test this, we measured sediment ATP levels at our regular faunal-sampling stations and at some additional stations (See Materials and Methods). Mean values ranged from 146 to 402 ng ATP ml^{-1} of sediment, with the exception of the area of intense seepage, which had a value of 809 ng ATP ml^{-1} sediment. We used whole sediment for these determinations so macro- and meiofaunal components are included. These results are consistent with our hypothesis of trophic enrichment.

DISCUSSION

The large, unresolved, complex mixture that makes up the Isla Vista seep oil is characteristic of an oil that has been severely weathered or bacterially degraded (Blummer et al, 1973; Reed and Kaplan, 1977). However, the presence of the low-molecular-weight components are in direct conflict with this idea. Simple weathering cannot explain the hydrocarbon distribution. Perhaps the low molecular weight components result from constant and preferential seepage from depth, while the higher molecular weight components have a sufficiently long residence time in the sediments to allow weathering or bacterial decomposition.

Results presented here confirm our earlier findings of a highly diverse benthic community that is associated with the oil seep and that is significantly denser than at the comparison area. The additional data presented on community dynamics over a two-year period show that community structure fluctuates little despite seasonal and interstation density differences. The relatively greater fluctuations in density at the seep suggest a lower community stability. These larger fluctuations also appear to be associated with a higher replacement rate for common species, another indication of lower stability.

Care should be taken in interpreting these results. Despite indications of community instability at the seep area community structure is relatively constant. This could be interpreted as the predominance of mechanisms that preserve community structure (i.e., predation and competition) over the inherent instability posed by high differential replacement rates. In this view, manifestations of relative instability in the seep community are sub-threshold phenomena.

Because of the proximity of the two test areas and the general east-to-west currents, these areas probably recruit planktonic larvae from the same water masses. Depth and sediment type are similar. We, therefore, suggest that the presence of fresh oil in the sediments, directly or indirectly, makes the seep more attractive to settling larvae. The large number of species with planktonic larvae might account for the larger fluctuations of organisms in the seep area. Such a phenomenon would also support our hypothesis of trophic

enrichment, because organisms supported by a trophic system with significant amounts of hydrocarbon and sulfide utilization presumably would be attracted to such areas. The finding of high levels of ATP in the sediment near areas of intense seepage also supports our hypothesis of trophic enrichment. The partitioning of benthic biomass among microbial meiofaunal and macrofaunal components that are in intimate association with intense seepage is currently being investigated.

Despite the low toxicity of seep oil, exposure levels and body burdens need to be established for seep organisms. For instance, what are the levels of aromatic compounds (such as ethyl benzene and isopropyl benzene) in bottom water, interstitial water, sediments, and tissues? High exposure levels or tissue levels of toxicants would need to be related to sublethal effects and would further implicate adaptive mechanisms. The apparent lack of benzene in the seep oil might partially account for the relatively low toxicity of this oil. Caldwell et al. (1977) showed that in chronic exposures of crab larvae to Cook Inlet crude oil (water-soluble fractions), benzene accounts for 30% of the toxicity. Clearly, further assays using benzene-supplemented seep oil are needed to determine how much of the toxicity can be related to this difference.

These comparative studies should be extended to other crude oils as well. This information together with results of studies on adaptation and on exposure levels and body burdens of seep organisms could be used to establish a generic picture for the effects of sediment-bound oil.

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EFFECTS OF CHRONIC CONCENTRATIONS OF PETROLEUM HYDROCARBONS ON GONADAL MATURATION IN STARRY FLOUNDER (PLATICHTHYS STELLATUS [PALLAS])

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ABSTRACT

Adult starry flounder, during gonadal maturation, were continuously exposed to low concentrations (100 to 200 ppb) of the water-soluble fraction (WSF) of Cook Inlet crude oil for periods of 5, 7 and 21 days. Daily observations of behavior were made and fish were subsampled to determine effects on their gonads and other organs. Accumulations of low-boiling-point aromatic hydrocarbons were measured in the gonad and liver.

Female flounders accumulated a mean concentration of 12.98 μg/g (ppm) monocyclic, cyclohexane and dicyclic components in mature ovaries, 113 times the water column concentrations.

Several changes in behavior and histological damage in ovaries and livers were attributed to chronic doses of WSF. Egg maturation was accelerated and abnormal and dead eggs were observed in both immature and mature ovaries of exposed females. Maturation of male testes was also accelerated. Extensive vacuole formation was found in livers from exposed flounder.

If such effects also occur in the field at chronic levels, low concentrations of oil could have serious consequences on natural populations. If marine organisms prove generally to be more sensitive during their spawning season, fishery management decisions should consider timing of oil-related activities to adequately protect fishery resources.

INTRODUCTION

In recent years, oil spills and tanker accidents have shown a need for greater knowledge of the effects of oil on marine biota. Perhaps of greater concern than catastrophic incidents, however, is increasing chronic oil pollution, particularly in estuaries with continuous boat traffic, recurring minor spills associated with oil transport, and ongoing discharges of municipal and industrial effluents.

Estuaries are important habitats in the life histories of many fishes and sustain important commercial and recreational fisheries. Several species migrate into shallow waters off estuaries (e.g. starry flounder; Orcutt 1950) or through estuaries to spawn (e.g. salmon, striped bass). Estuaries are also important nursery areas for the young stages of many fish. Therefore, many species cannot avoid being exposed to chronic concentrations of pollutants during critical and sensitive life history stages.

Previous work at Tiburon Laboratory showed that prespawning Pacific herring were adversely affected by lower concentrations (100-800 ppb) of benzene than were egg and larval stages (which were adversely affected only at ppm concentrations). Adult herring exposed prior to spawning exhibited erratic spawning behavior, spawned prematurely, and suffered gonadal egg death. Survival of gonadal eggs and larvae to hatching and through yolk absorption was decreased by 50 percent (Struhsaker 1977).

The purpose of the experiments conducted and described here was to examine the effects of low concentrations of the WSF of Cook Inlet crude oil (approximating a chronic field concentration) on female and male starry flounder prior to spawning. An attempt was made to relate these effects to concentrations of the low-boiling-point aromatic and alkyl cyclohexane components accumulated in the gonadal and liver tissues; primary emphasis was given to the low-boiling point, monocyclic and dicyclic aromatic components of the water-soluble fraction (WSF) of crude oil because these components comprise a major portion (50-90%) of the water-soluble fraction (WSF) of several crude and refined oils (Anderson et al. 1974b) and are also relatively toxic.

METHODS

Fish:

Starry flounder, Platichthys stellatus (Pallas) were collected from inshore areas near Bodega Bay, California. Fish were captured with an otter trawl by personnel of the California Department of Fish and Game and were transferred to 1900-liter tanks at Tiburon for acclimation.

Flounder were not fully ripe when captured, and were in varying stages of maturation prior to spawning. Standard lengths, wet weights of adults, lengths and weights of gonads and other morphometric data of the fish used in the experiments are summarized in Table 1. The primary

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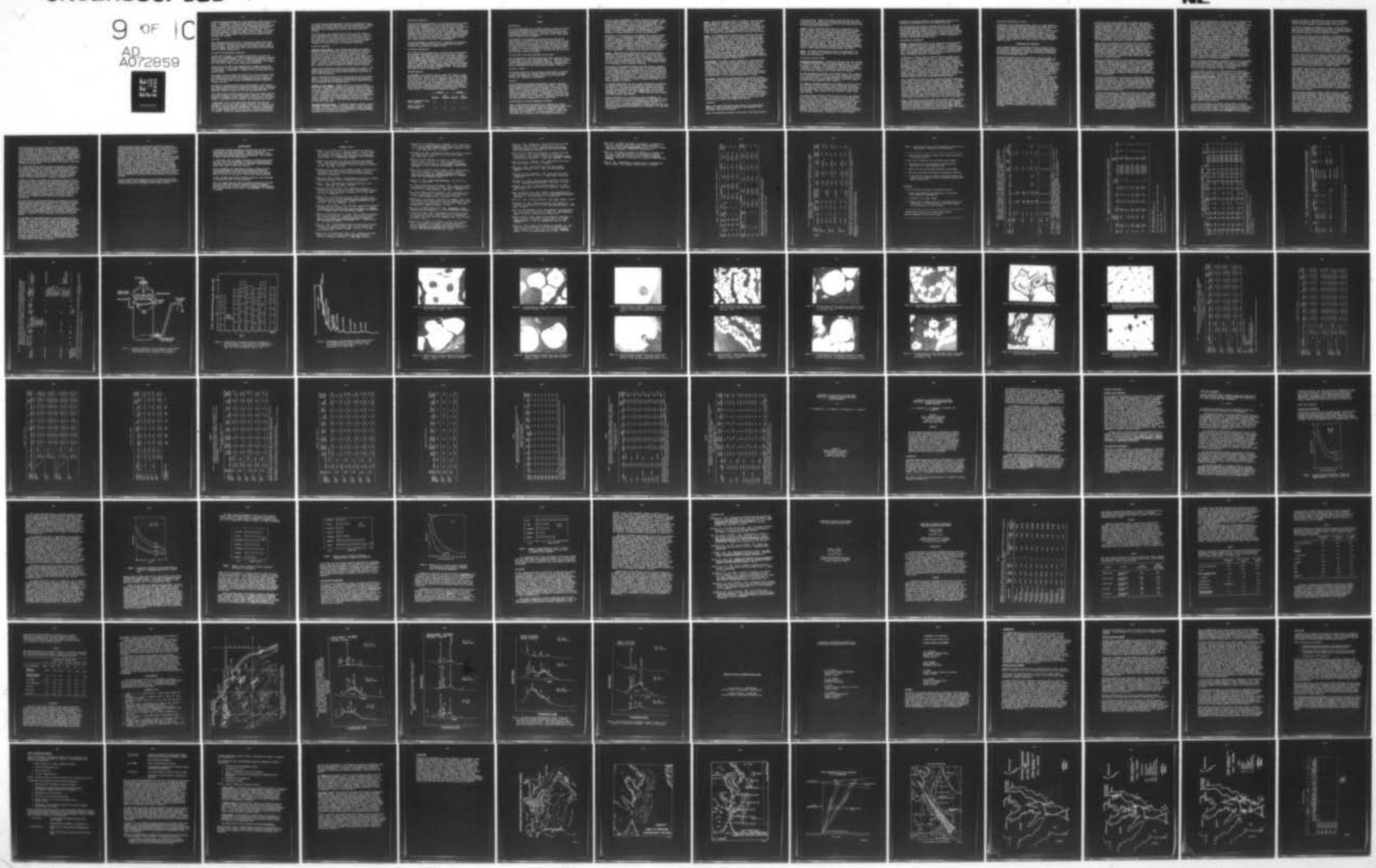

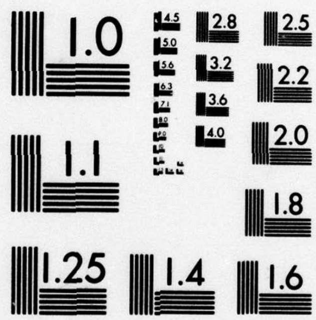

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difference between experiments was in the percentage of adults with maturing gonads. In Experiment 1 (January) females were in earlier maturation stages. In Experiment 2 (February) most females were maturing and in late maturation stages; the males were all ripe. Throughout the experiments we were unable to obtain ripe-running females from the field, so in Experiment 3 (April) an attempt was made to induce spawning. This experiment was unsuccessful, because most females were in a refractory period (resting stage). Males, however, were ripe and some results from this experiment are reported.

Apparatus:

Three experiments were performed in a continuously flowing system using dosing apparatus developed by project personnel (Benville et al., manuscript in prep.). This apparatus (Figure 1) produced a stable outflow of the water-soluble fraction of Cook Inlet crude oil which could be diluted easily to desired concentrations.

Acclimation and Experimental Conditions:

Flounder were acclimated to experimental conditions for at least two weeks prior to experimentation. The experiments were conducted at ambient levels at the time of testing (Table 2). The mean temperatures for the three experiments were 10.7, 13.7, and 17.2°C, respectively. The flounder were fed a diet of squid and bay shrimp during acclimation.

Because they do not feed during spawning and the exposure periods were relatively short (5 and 7 days), flounder were not fed during the first two experiments. In Experiment 3, flounder were fed the last week of the exposure period.

Test groups of starry flounder were placed in each of two 866 liter fiberglass tanks; one tank received a continuous flow of WSF in seawater at a mean concentration from 115 to 221 ppb (depending upon which experiment, Table 2). The other tank received uncontaminated (control) seawater at the same flow rate.

Flounder were continuously dosed during experimentation. Water samples were taken and analyzed daily to determine the concentration of low-boiling-point hydrocarbons in each of the tanks and the dosing apparatus effluent. Temperature, salinity, oxygen, and flow rate were monitored daily.

Daily observations of behavior included ventilation rate (number opercular beats/min), estimation of ventilation volume, regularity of ventilation, estimation of swimming activity, "digging" or escape activity, and feeding behavior. Ventilation rate was measured; other parameters were ranked.

In Experiments 1 and 2, two flounder were taken daily from each tank (exposed and control) for autopsy, chemical analysis, and histology. In Experiment 3, all flounder were autopsied at the end of a 3-week exposure. All fish were weighed, measured and dissected. Macroscopic examinations of all organs were made and the ovaries, testes, liver and gall bladder were removed. Gonads were weighed, measured and examined microscopically

to determine general maturation stage, presence of opaque dead or necrotic eggs, and the gross appearance (color and deliquescense). Maximum egg diameters of 10 eggs from the ovary of each female were measured. Spermatozoa from ripe males were examined under the microscope for motility.

The ventral gonad, gall bladder and half of the liver were placed in clean, preweighed glass culture tubes or glass sample jars. The tubes were sealed tightly with teflon-lined screw caps, the bottles with foil-lined caps. All samples were frozen until they could be analyzed. The dorsal gonad and other half of the liver were preserved in 10% formalin in 1% calcium chloride for histological preparation.

Analytical Procedures:

Analysis of Water Samples. Water samples taken daily from exposure tanks were analyzed for monocyclic aromatic hydrocarbons by extracting one liter twice with 10 ml of TF-Freon and injecting 3.2 microliters of each extract into the gas chromatograph (column packed with 5% SP-1200 and 5% Bentone 34 on 100/120 supelcoport). Liter samples taken daily from solubilizer effluent flowing into the exposure tanks were extracted 3 times with 10 ml of TF-Freon and extracts were injected into the GC. The limit of detectability for monocyclics in water was 0.010 mg/L. In addition, one-liter solubilizer samples were extracted with 80 ml methylene chloride for analysis of dicyclic aromatic compounds.

Extracts were concentrated to about 10 ml and stored in a freezer. Subsequent preparation for analysis followed procedures of MacLeod et al. 1977 and were analyzed on a 10-foot column packed with 5% SP-2100, 1% BMOT on 100/120 supelcoport.

Alkyl cyclohexanes and dicyclics were undetectable in tank water column samples. For results reported here, the concentration was estimated from the concentration in solubilizer effluent and by calculating final tank concentration with the dilution factor.

Analysis of Tissue Samples. Samples analyzed for dicyclic aromatic hydrocarbons and aliphatic compounds were processed according to MacLeod et al. 1977. Samples were analyzed for monocyclic aromatic and alkyl cyclohexane hydrocarbons using procedures developed by project personnel for these experiments (Table 3). In some samples, insufficient weight of tissue (particularly immature gonads) was available, and samples were pooled. In instances where sample weights were below the optimum 10 g, tissue concentrations may be underestimated, particularly of less abundant components. Also, a few liver sample extracts were emulsified and could not be analyzed.

Additional Chemical Analyses. The National Analytical Facility, Seattle, Washington, performed a number of analyses of water, tissue, and crude oil samples by capillary column gas chromatography or mass spectrometry to verify results obtained by in-house analysis and to identify unknown hydrocarbons in tissue and water extracts.

Histological Technique:

Ovaries preserved in 10% formalin in 1% calcium chloride were prepared especially for examination of the lipid distribution in the eggs following the recommendation of Bucke (1972) and using the procedure in Humason (1972). Frozen sections (16 µ) were cut with a cryostat, because routine processing methods would remove lipids. Sections were stained with an oil soluble dye, Oil Red O, counterstained with Harris' Hematoxylin and blued in Scott solution. Staining times were adjusted according to the maturation stages, which varied in stain affinities. One series of sections from each sample was stained with Oil Red O only, another series with Oil Red O and hematoxylin.

Livers were embedded in paraffin and 10 µ transverse and longitudinal sections made. Sections were stained with hematoxylin and eosin according to the procedure in Humason (1972).

Histological Examination:

Each slide was first examined under a low-power (4X or 10X objective) phase contrast microscope and searched for the presence of dead or abnormal eggs. One hundred eggs were counted and closely examined and the percentage dead or abnormal determined. The maximum diameter of the five largest eggs was measured, and the maturation stages ascertained after a complete assessment of all cytological structures occurring at that stage. The maturation stages determined by Yamamoto (1956) for eggs of the flounder, Liopsetta obscura, were found applicable and used in this analysis (11 stages in all). Photomicrographs were taken of control and exposed eggs.

Spawning Induction:

In Experiment 3, an attempt was made to induce the flounder to spawn. Most flounder were adults, but they appeared to be in a post-spawning refractory stage. The technique of Smigielski (1975 a, 1975 b) using carp pituitary (5 mg/454 g total wet weight) in physiological saline solution was employed. Fish were marked with colored thread through the caudal fins so behavior of individual fish could be observed. It was not possible to distinguish sexes in the species with certainty, thus 8 fish were selected at random and injected with carp pituitary, 8 fish were not. The experimental design was as follows:

	Control		Exposed	
	Injected	Not Injected	Injected	Not Injected
Exposed immediately after first injection	2	2	2	2
Exposed 1 week after first injection	2	2	2	2

RESULTS

Morphometrics:

Fish in all experiments were in similar condition. However, more fish in the second experiment were maturing and few females in the third experiment were maturing (Table 1). There were no significant differences between condition for exposed and control fish or length-weight ratios of gonads in the experiments.

The "eyedness" of the flounders was recorded because this genetic feature varies in frequency between populations and with age. For the sample in Experiments 1 and 3, there were approximately 50% right-eyed to 50% left-eyed flounders (Table 1), but more large fish were right-eyed than left-eyed. The differential survival of right-eyed flounder is thought to indicate a physiologically hardier type (Orcutt 1950). In Experiment 3, a higher proportion of the sample was left-eyed; there were more small males in this sample.

Concentrations of Petroleum Components in Test Tanks:

Mean concentrations of petroleum hydrocarbons (WSF) ranged from 115 to 221 µg/L (ppb) in the three experiments (Table 2). Individual component concentrations are given in the Appendix (Table A). Only monocyclic aromatic hydrocarbons were detectable in test tanks, although traces of alkyl cyclohexanes were seen in some samples (Appendix, Table E).

Mortality - Adults:

No mortality occurred at the low exposure concentrations, as expected. In other experiments with flounder, exposed with similar apparatus, mortality was observed at concentrations as low as 1.0 mg/L (ppm) (Yocom et al., manuscript in preparation).

Behavior:

Several behaviors were observed and measured. Usually, individual variation obscures significant treatment differences. In all experiments, however, there was an initial elevation of ventilation rate in exposed fish over that in controls for periods of 2 to 4 days. Eventually, rates of exposed fish dropped and the ventilation rates of exposed and controls were similar. In Experiment 3, the mean ventilation rate of exposed flounder was 45.1 beats/min after the first week and that of controls was 35.7 beats/min. Irregular ventilation rates were also observed in exposed and not in control fish.

Concentrations of Petroleum Components in Tissues:

Tissue concentrations and accumulations of components in ovaries, testes, livers and gall bladders are given in the Appendix (Tables A-E). Means and ranges of monocyclics, alkyl cyclohexanes and dicyclic components are also summarized in Table 4. In Table 4, monocyclics are grouped into monocyclics 1 (M-1) and monocyclics 2 (M-2). The first group (M-1) includes the lowest-boiling-point monocyclics:

benzene, toluene, ethylbenzene, p-xylene, m-xylene and o-xylene. The more substituted monocyclics (M-2) included isopropyl benzene, n-propyl benzene, total C_3-benzenes, total C_4-, and total C_5-benzenes. Alkyl cyclohexanes (CH) identified include methyl cyclohexane, cis 1, 3 dimethyl cyclohexane, 1, 2 dimethyl cyclohexane and a C_3 cyclohexane. Three other unidentified components are probably also C_2 and C_3 cyclohexanes. Dicyclics indentified (D) include naphthalene, 2-methyl naphthalene, 1-methyl naphthalene, and total C_2 naphthalenes.

Monocyclics 2 (M-2) and dicyclics were analyzed only in mature ovaries in Experiment 2. All monocyclics, cyclohexanes, and dicyclics were analyzed in tissues of Experiment 3. Since fewer maturing ovaries occurred in Experiment 1, not all of these samples were analyzed. Monocyclic concentrations in maturing ovaries were similar to those in Experiment 2. Other experiments (Yocom et al, manuscript in preparation) indicated no detectable levels of any components in 120 tissue samples from control flounders. Therefore, only a few controls were analyzed in these experiments. No components were detected in any controls.

Ovaries. Immature ovaries accumulated much lower concentrations of monocyclics and alkyl cyclohexanes (mean total - 0.890 μg/g; Table 4) than mature ovaries (mean total = 8.585 μg/g monocyclics and alkyl cyclohexanes; 12.976 μg/g all monocyclics, cyclohexanes, and dicyclics; Table 4). Uptake of components was rapid, near maximum concentrations occurring after 24 hours of exposure (Figure 2). The maximum accumulation of components in any ovary was 14.618 μg/g.

Proportions of the components remained relatively constant throughout the experiment (Figure 2). The accumulation of alkyl cyclohexanes was of some interest, since these components have not previously been identified as biologically active components of crude oil and yet appear in relatively high concentrations in both ovarian and liver tissues (Yocom et al, manuscript in preparation-b). A gas chromatogram of the freon extract of adult starry flounder ovary exposed for approximately 7 days (Exp. 2) is shown in Figure 3; individual monocyclic and alkyl cyclohexane components are labeled.

The maximum accumulations over water column concentrations are given in the Appendix (Tables A-E), and are summarized in Table 4 and Table 5 (ovaries only). The maximum accumulation was determined by dividing the tissue concentration by the water concentration. In the case of components not detected in tank water samples (monocyclics and alkyl cyclohexanes < 0.010 mg/g; dicyclics < 0.00025 mg/g) the tank concentrations were estimated (see Methods).

Maximum accumulation of all monocyclics, alkyl cyclohexanes, and dicyclics in mature ovaries was approximately 80 to 200X (mean = 112.8X) and of monocyclics (M-1 only) and cyclohexanes was approximately 50 to 160X (mean = 74.6X) the water concentration (Tables 4 and 6). In immature ovaries, the maximum accumulation of monocyclics (M-1 only) and and alkyl cyclohexanes was approximately 3 to 10X (mean = 7.7X) the water concentration.

Testes. There were no immature males in the samples. Testes of mature males accumulated no detectable levels of components after 1 week of exposure (Table 4). However, after 3 weeks of exposure (Appendix, Table D) 0.313 to 1.361 μg/g of toluene accumulated in the testes. No other component was detectable. Uptake in the testes was low and much slower than in ovaries. The maximum accumulation of toluene after 3 weeks of exposure was approximately 3X to 6X the water concentration.

Livers. The concentrations of monocyclics (M-1 only) and alkyl cyclohexanes were determined after 1 week of exposure for livers of both males and females (Table 4). Mean concentrations of these components were 8.450 μg/g in mature males, 15.535 μg/g in mature females, and only 1.346 μg/g in immature females. Data over the 1-week test period indicate an increasing concentration with time, thus uptake does not reach a maximum level rapidly as in the case of the gonads. After 1 week of exposure mean maximum accumulations in mature adults were approximately 70X (males) and 135X (females) the water concentration (Appendix, Tables A-C). After 3 weeks of exposure, maximum monocyclic accumulations were approximately 200X to 400X (immature females) and 225X to 290X (mature males) the water concentration (Appendix, Table D). Maximum accumulation of cyclohexanes was approximately 2600 to 8750X the water concentration (Appendix, Tables B and E).

Gall Bladders. The weight of tissue available for component analysis in gall bladders containing bile was insufficient in most cases, but analysis of monocyclics and cyclohexanes in gall bladders of fish in Experiment 2 (Appendix, Table A) showed that the concentration was approximately the same in gall bladders of males and females and did not significantly increase throughout the 7-day exposure period (0.280-0.469 μg/g). Only toluene was present, no other monocyclics or cyclohexanes were detected. The maximum accumulation in gall bladders was approximately 2 to 4X the water concentration of toluene.

All Tissues. Among the six monocyclics (M-1), the relative accumulation of toluene was the highest, generally followed by m-xylene, benzene, o-xylene, ethylbenzene and p-xylene, respectively. Of the cyclohexanes (CH), methyl cyclohexane reached highest concentrations, followed by cis 1, 3 dimethyl cyclohexane, and 1, 2 dimethyl cyclohexane. Among the more substituted monocyclics (M-2) the highest concentrations were of the C_3-benzenes, followed by C_4-benzenes and C_5-benzenes, respectively. And finally, among the dicyclics (D), naphthalene was highest in concentration followed by 2-methylnaphthalene and 1-methylnaphthalene, respectively. These general proportions were approximately the same in liver tissues of both sexes. In mature ovaries, however, the relative abundance of monocyclics was slightly different than in livers, the concentration of benzene being higher than m-xylene.

Autopsies:

Liver. Some exposed fish showed gross effects in the appearance of the liver. After a few days of exposure, livers appeared to have hemorrhagic areas and were mottled.

There was considerable variation in liver color, from bright yellow to

dark red (Table 1). There was no obvious correlation with sex, size or exposure to WSF. There is an indication that the color variation is associated with gonadal maturation, with fewer fish having yellow livers at later maturation stages (Table 1).

Ovaries. Exposed fish showed some effects in the appearance of the ovary. Exposed ovaries were paler yellow than controls of equivalent maturation stage. These ovaries also contained some opaque white eggs, visible on the surface, appearing to be necrotic foci with several dead eggs when examined microscopically. The capillary network over the ovarian membrane of exposed fish contained blood, but the network appeared paler red than in controls. Microscopic examination indicated hemolysis of red blood cells had occurred, lending to the overall paler appearance of exposed ovaries. There were dead eggs seen in most of the maturing ovaries (Table 6). Dead eggs were not obvious in immature ovaries. Because the differences between control and exposed fish were subtle, further comparison was made histologically (see below).

Testes. No obvious differences were noted in the appearance of the testes. No difference in spermatozoan motility between control and exposed males was measured.

Histological Effects on Eggs:

Abnormalities and Mortality. Abnormal and dead eggs were first observed in immature and maturing ovaries of exposed females by day 2 of the exposure (Table 5, Table 6). These abnormal and dead eggs were observed throughout the remainder of the experiment. Ovaries of fish examined 1 week after the cessation of exposure and depuration had the most dead and abnormal eggs, indicating that effects were not reversible.

The mean percentages of abnormal eggs in exposed were 13.2% in immature and 3.0% in mature females of Exp. 1 and 0.5% in immature and 13.0% in mature females of Exp. 2. The mean percentages of dead eggs were 5.5% in immature and 5.8% in mature females of Exp. 1 and 0.2% in immature and 15.0% in mature females of Exp. 2 (Table 7).

The commonest abnormality observed in both immature and mature eggs was the occurrence of clear vacuoles extruding through the cytoplasm of the egg, usually near the periphery (Figs. 4B, 5B, 6B). The vacuoles were colorless with oil red O staining, indicating that they are not lipid deposits. These vacuoles were never observed in control eggs (Figs. 4A, 5A).

Dead eggs in immature ovaries occurred in necrotic foci, and appeared to be atresic (Figs. 7B, 8A, 8B). By the end of the exposure period, and particularly after the subsequent depuration period, reduced numbers of eggs appeared to occur in exposed immature ovaries compared to controls (Figs. 7A and B), possibly indicating resorption. The first change appeared to be coalescence of nucleoplasm into fewer droplets (Fig. 8A) until only one droplet was present, the nuclear membrane still intact. The coalesced droplet had a different staining affinity, appearing purple rather than blue as do nucleoli of controls and unaffected exposed eggs. Subsequently, the nuclear membrane

disappeared, the droplet remaining, with simultaneous necrosis of the cytoplasm and disintegration of the cell membrane (Fig. 8B).

Dead maturing eggs also occurred in necrotic foci (Fig. 9B). The eggs were disintegrating and appeared to have thicker cell membranes (zona radiata) than the intact controls (Fig. 9A). With red oil O staining, yolk globules appeared a darker red-brown color than the normal red-pink globules of control eggs. Although present in exposed ovaries, the foci of dying and dead mature eggs were difficult to detect histologically with only a few sections from each ovary.

Acceleration of Maturation:

Females. Another apparent effect is the acceleration of egg maturation in exposed flounder over that in controls (Table 7). The stages of Yamamoto (1956; 1-11) were used to assess maturation so that differences between controls and exposed attributable to different maturation stages would not be confused with the effects of exposure. A complete description of egg maturation in starry flounder will be published separately (Bowers and Whipple, manuscript in preparation).

In Experiment 1 (January; Table 5) immature ovaries contained eggs in stages 1 to 3 (1 = chromatin-nucleolus, 2 = early perinucleolus, and 3 = middle to late perinucleolus). Maturing ovaries were in stages 4 and 5 (yolk = yolk vesicle, and 5 = primary yolk stage). In Experiment 2 (February; Table 6) immature ovaries were in stages similar to those in Experiment 1 (stages 1 to 3). In maturing ovaries, however, control eggs were predominantly in stage 6, or 6 to 7 (6 = secondary yolk stage, 7 = tertiary yolk stage). None had reached the full tertiary yolk stage (7). Among the exposed, several ovaries showed eggs in later stages 7 and 8 (7 = tertiary yolk stage and 8 = migratory nucleus stage). Maturing flounder contain eggs in two stages, having eggs in perinucleolus stages as well as the predominant maturation stage.

Table 7 summarizes the means of several parameters showing acceleration of maturation in ovaries of exposed flounder for Experiment 2. An indication of acceleration of maturation in females of Experiment 1 was also noted. Table 7 shows that ovaries of exposed maturing females not only had a higher frequency of more advanced maturation stages, but also that the mean maximum egg diameter was greater. These observations correlate with the higher gonadosomatic index (GSI) in exposed (6.59) than in control (5.64) females. Since the GSI is based on the ratio of ovary weight to body weight and because relatively small females contained advanced maturation stages, the indication is that acceleration in maturation was due to exposure and not a function of the size of the female.

Males. Histological sections of testes were not made. However, the GSI of males also indicated an acceleration of maturation due to exposure. Sample sizes of males in Experiments 1 and 2 were too small. However, the males in Experiment 3 (exposed for 3 weeks) had a higher mean GSI (0.387; n=5) than did controls (0.140; n=7). Further, 80% of the exposed males were ripe, while only 29% of the controls were ripe.

Histological Examination of Livers:

Examination of liver tissue showed that, after 5 to 7 days exposure to 115 ppb WSF, livers were highly vacuolated and the hepatic muralia were disorganized in both male and female flounders (Figs. 10B, 11B). Cytoplasmic vacuolization increased with exposure time. Similar effects were also seen in livers of flounder allowed to depurate for 1 week after the 1 week exposure period, indicating the effects may not be reversible, as the degree of vacuolization was greater. Sloughing of endothelial tissue in blood vessels was found in livers of some exposed flounder. These changes were not seen in livers of control flounder (Figs. 10A, 11A).

CONCLUSIONS AND DISCUSSION

Starry flounder exposed to approximately 100 ppb of the WSF of Cook Inlet crude oil exhibited several effects, including elevated activity and ventilation (respiration), erythrocyte destruction, abnormalities and necrosis in eggs and liver tissue, and acceleration of maturation in both males and females (Table 8).

Flounder were exposed only to WSF components in the water column. In the field, exposure could occur from two other routes; sediments and food. The exposure concentrations in these experiments (approx. 100-200 ppb) are probably higher than in the field. Although measurements of aromatics in natural waters are scarce, available field data show that chronic concentrations of total aromatics in water may reach levels of 1-30 ppb offshore (Clarke et al. 1977b; Hiltabrand 1978). Concentrations are probably higher in polluted estuaries. In addition, an exposure of 7 days is less than flounder would experience in a chronic field situation. Sediment concentrations of aromatic hydrocarbons (Clarke et al. 1977b) reach levels of approximately 1,000-60,000 ppb (wet wt.). Flounder would also be exposed to aromatics in sediments in chronically polluted areas. Field measurements of alkyl cyclohexanes in water or sediments are not available. Flounder could also be exposed to WSF components of petroleum through contaminated food. However, in later prespawning maturation stages, flounder do not feed (Orcutt 1950) and other experiments at our laboratory (Yocom et al., manuscript in preparation) show that when nonspawning adults were fed contaminated littleneck clams (8.0 µg/g M-1+CH), they accumulated 1.72 µg/g in their livers (CH only) compared to flounder exposed through the water column (0.100 mg/L M-1+CH) and fed uncontaminated clams, which accumulated 180.8 µg/g (M-1+CH). Lack of accumulation of the toxic aromatic fraction from food may partially explain the relatively few effects observed in rainbow trout exposed prior to reproduction to petroleum in their diet, as observed by Hodgins et al. (1977a). The major route of accumulation of the more toxic aromatics would appear to be through water column and sediment exposures. The exposure concentration in our experiments is probably a reasonable approximation to chronic exposure of flounder in the field.

No flounders died in these experiments, but behavior was affected. There was an elevation in activity and ventilation, indicating an increased respiration and metabolic rate. A return to control levels occurred subsequently. Similar results were obtained in other studies of larvae and adults of salmon, striped bass, and Pacific herring exposed to sublethal levels of benzene (Brocksen and Bailey 1973; Eldridge et al. 1977) and in other fish and invertebrates exposed to sublethal levels of WSF of crude and refined oil (Anderson et al. 1974a). The behavior of adult herring prior to spawning was greatly affected by exposure to ppb levels of benzene, including rapid ventilation, disequilibrium, and premature spawning (Struhsaker 1977).

Uptake and total accumulation of monocyclics (M-1) and alkyl cyclohexanes (CH) in gonads and livers of flounder varied with sex and maturity (Table 8). Highest mean accumulation occurred in livers of adult females with gonads in the resting stage (2800X; Yocom et al., manuscript in preparation) and lowest in immature females (12X). Mature males accumulated 74X and mature females 135X the concentration of M-1 and CH in the water. Concentrations increased with time in livers of all flounders, reaching much higher levels after 3 weeks than after 1 week of exposure.

Uptake and accumulation of M-1 and CH in gonads also varied with sex and maturity. Rate of uptake was much faster in mature ovaries than in livers, with maximum concentrations in about 24-48 hrs. Concentration levels of all components measured (M-1, CH, M-2, D) remained at an equilibrium level for the remainder of the exposure period. Maximum accumulation was highest in female ovaries (75X), lowest in male testes (not detectable). Ovaries of immature females and resting ovaries of mature females accumulated comparatively low concentrations (7X, 8X respectively).

Variation in accumulation in the liver may be related to feeding and resultant metabolic rates. Adult flounders in the resting stage were fed clams and probably had a faster rate of metabolism and uptake than did sexually maturing male and female flounders and immature females which were not fed. The variation in accumulation of lipid-soluble components in gonads is probably a function of the amount of lipid; maturing ovaries containing far more lipid than immature ovaries and testes containing even less lipid.

Although tissue samples are available for analysis of alkanes, we have not completed these analyses. Anderson (1974a) suggested that although alkanes and aromatic hydrocarbons are both accumulated, the aromatics are concentrated to higher levels and retained longer than the alkanes. Kühnhold et al. (see paper in this proceedings) found that winter flounder accumulated relatively low concentrations of alkanes from low ppb levels of No. 2 fuel oil after long exposures while accumulating higher levels of aromatics. Alkanes are believed to be less toxic than aromatics, although more recent work suggests they may have narcotic effects and cytotoxicity (Clarke et al. 1977a).

The highest total concentrations in ovaries were of M-1, followed by CH, M-2 and D. The proportions of M-1, CH, M-2 and D remained fairly constant in mature ovaries over the exposure period. In livers, however, the relative proportions of M-1 and CH changed, with cyclohexanes increasing relative to monocyclics with time. Concentrations of individual components in mature ovaries after 7 days of exposure were as follows, in decreasing order: methyl cyclohexane, toluene, benzene, C_2 cyclohexane (unidentified #1), m-xylene, Cis 1, 3 dimethyl cyclohexane, ethylbenzene, 1, 2 dimethyl cyclohexane, C_3 cyclohexane, o-xylene, C_3 cyclohexane (unidentified #3) and p-xylene. Mean total accumulation of alkyl cyclohexanes after 7 days of exposure was much higher than of monocyclics-1 (890X, 68X water concentration, respectively). The high accumulation of cyclohexanes in ovaries and livers from undetectable levels in water is of interest since they have not been previously identified as biologically active components. The toxicity of the cyclohexanes is not well known. Some data indicate that they are as toxic to fish as are monocyclic aromatics (Pickering and Henderson 1966), but information is so incomplete that no definite statement can be made. The mean total accumulation of M-2 and D in ovaries after 7 days of exposure was approximately 260X water concentration. Highest concentrations of individual M-2 and D components in mature ovaries were of methylated naphthalenes.

When the relative concentrations of components in both liver and gonadal tissues are compared to concentrations in the water, it is apparent that differential uptake has occurred. Many components are undetectable in the water column but accumulate to very high levels in the liver and gonads, particularly the alkyl cyclohexanes.

A recent review by Clarke et al. (1977b) shows that few laboratory experiments have been done on the accumulation of toxic WSF components in ovaries or testes of fish. Work by Zitko (1971) on the flounder, Pseudopleuronectes americanus, showed a total aromatic concentration of 622 μg/g wet weight in the "guts" of flounder exposed to Bunker C. Previous work at the Tiburon Laboratory, with herring exposed to 100 ppb benzene prior to spawning, showed a concentration of 1.2 μg/g wet weight benzene in mature ovaries after a 48-hr exposure. This is comparable to the uptake of benzene in mature ovaries of flounder (1.27 μg/g) after 48 hrs. In addition, few laboratory experiments measuring accumulation of monocyclics in specific tissues have been made. Korn et al. (1976-1977) measured uptake of radioactive labeled benzene in several tissues (not mature ovaries) of northern anchovy, striped bass and Pacific herring. Residues of benzene and toluene in liver tissue of herring are comparable to those measured here in flounder, with toluene reaching higher concentrations than benzene. Clarke et al. (1977b) summarizes a few other laboratory studies on uptake in fish and tissue levels of other aromatics.

In the review by Clarke et al. (1977b), tissue levels of aromatics measured in field-captured fishes show that from 0.4 to 22 μg/g wet weight occurred in whole tissue. Zitko (1971) measured 21 μg/g aromatics in the "guts" of field specimens of P. americanus exposed to Bunker C. These data indicate that tissue levels of aromatics in field-captured

flounder correspond to those measured in starry flounder exposed to 100 ppb of the WSF of crude oil in this study (liver = 1-20 μg/g in 7 days), and that comparable deleterious effects may also occur.

The effects of exposure are summarized in Table 8. Most effects are similar to those described by Couch (1975), Walsh and Ribelin (1975) and Smith and Cole (1973) for pesticide exposures and are probably generalized sublethal responses of fish to hydrocarbon exposure.

Some effects on the liver, such as disruption of the organization of hepatic muralia and increased lipid deposition could have been accentuated by the 7-day exposure period when flounder were not fed. However, these effects were not observed in control livers. Further, maturing fish normally do not feed. Starvation stress may have interacted with the petroleum stress to produce the pronounced effects on livers of immature fish. Similar tissue effects were observed in livers of English sole exposed to oiled sediments (McCain et al. 1978) and of rainbow trout exposed to oil in food (Hodgins et al. 1977a). Other histopathological effects of oil were reviewed by Hodgins et al. (1977b).

The WSF of Cook Inlet crude oil resulted in both direct and indirect effects on starry flounder in the various maturation stages (Table 8) (see also Kühnhold et al., this proceedings). There were direct effects on eggs (necrosis and abnormalities) which may have indirectly reduced subsequent fertilization, hatching, larval growth and survival. There also appeared to be an indirect effect on hormones promoting gametogenesis, with maturation accelerated in exposed flounder.

There seemed to be no effect of exposure on testes or sperm motility in mature males. However, tissue sections of testes were not made, and subsequent work may reveal effects on a cellular level. Numerous changes in eggs from exposed fish at all stages were noted, including egg death. In immature eggs, the apparent death or disintegration of eggs may have been due to atresia or resorption. A few atresic eggs were observed in control immature females also, although the effect was more pronounced in exposed immature females. As in the liver, atresic eggs in immature females may result from interaction of starvation stress with petroleum stress. Egg abnormalities consisted largely of vacuolization; never observed in eggs from controls. The vacuoles may result from an effect of petroleum hydrocarbons on osmoregulation and the hydration of ovaries.

Maturation was accelerated in exposed flounders (Table 8). Exposed males had higher gonadosomatic indices and a higher percentage of testes undergoing spermiation. Exposed females contained eggs in later maturation stages than control eggs, with increased vitellinogenesis (yolk globules = vitellin = phosolipids; Yamamoto, 1957) and larger egg size. The gonadosomatic indices of exposed females were also higher than controls. An explanation of the acceleration in maturation involves the observation that detoxification of petroleum hydrocarbons requires enzymes of the mixed-function-oxidase (MFO) system which also hydroxylate steroids and are involved in pre-oxidation of lipids. The MFO enzymes, bound to the ribosomes, function in several biochemical pathways of organisms. 17-α-hydroxyprogesterone is the major hormone

inducing maturation of eggs in female winter flounder (Campbell et al. 1976) and normally undergoes hydroxylation to adrenocortical steroids in the MFO system. If aromatic and cyclohexane components competitively inhibit this function, they may potentiate the effect of progesterone thus accelerating egg maturation. Simultaneously the oil components may inhibit the pre-oxidation of lipids and the formation of adrenocortical steroids, affecting water balance and lipid deposition. Similar competitive inhibition of toxicants occurs in mammals (LaDu et al. 1972; Doggett et al. 1977) and may also function in fish exposed to petroleum (Brocksen and Bailey 1973).

The tissue-level effects seen at the end of the exposure period were also present after 7 days of depuration, and appear to be irreversible. The results of Kühnhold et al. (see paper, this proceedings) also indicate that this does occur, with reductions in survival and growth of later stages. A 50% reduction in fecundity, and larval survival through hatching and yolk absorption, was also observed in herring exposed to low ppb benzene prior to spawning (Struhsaker 1977).

A number of studies of the effects of petroleum have shown an initial stimulation of several parameters when organisms are exposed to low sublethal levels, while at higher acute levels a depression or narcosis occurs (Brocksen and Bailey 1973; Anderson 1974a; Eldridge 1978). This phenomenon was described by Smyth (1967) as a sufficient challenge. An example cited was increased growth at low exposure levels of pesticides. However, stimulation by toxicants may not be ultimately beneficial to the organism, as demonstrated here. Also, with chronic exposures, the ability of the organisms to homeostatically adjust may collapse or there may be an energy depletion resulting in decreased growth or reproduction.

The cause-and-effect relationships between the components of crude oil measured in these tissues and the physiological or histological effects observed cannot be ascertained definitely. It is difficult to demonstrate which components or interacting components are exerting the primary effects. That a single component can produce similar effects in herring has been discussed previously (e.g. benzene, Struhsaker 1977). Finally, it is not clear whether the toxic effects are caused by the unchanged components or their metabolites, as pointed out by Malins (1977).

In conclusion, the preliminary results of these experiments indicate strongly that low levels of the WSF of crude oil, approximating chronic exposures, can result in deleterious effects that reduce the fecundity of flounder. The total reduction in survival through spawning, hatching and larval stages cannot be assessed, but results indicate a probable reduction in viable eggs of approximately 15-30%, assuming abnormal eggs will not survive. In herring, the reduction in survival through yolk absorption was estimated as 50% (Struhsaker 1977). These effects occur at concentrations two orders of magnitude less than the acute 96-hr TLMs. Further, if exposure to oil stimulates gametogenesis and spawning, spawning fish may be induced to release eggs in areas of high petroleum concentrations (e.g. oil spill), thus exposing relatively sensitive stages to the effects of the oil.

Although sublethal effects of petroleum on individual organisms in small subsamples have been demonstrated readily in laboratory studies, evidence for these effects occurring in organisms in the field on a population level has been more difficult to provide. Natural variation in population sizes of most species often obscures variation due to a pollutant. Few "fish kills" have been irrefutably linked with a specific pollutant or spill event, particularly in estuarine situations. We suspect, however, that slow population declines of several estuarine-dependent species may be at least in part due to the interaction of chronic pollution with normal environmental stress, such as occurs during spawning. A gradual decline in production of the population may take the form of reduced growth or in the inhibition of reproduction. The latter may occur if spawning years are missed, egg production is reduced, and egg viability decreased. An assessment of the reduction in survival of gonadal eggs by exposing fish in the laboratory prior to spawning enables us to obtain a more direct estimate of the potential reduction in year-class survival attributable to a particular pollutant.

If marine organisms prove generally to be more sensitive during their spawning season, fishery management decisions should consider timing of oil-related activities to adequately protect fishery resources.

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Table 1. Morphometrics of starry flounder subsamples. Experiments 1, 2, 3.

Exp. No. Date	Tot. No.	Fem. No. (%)	Male No. (%)	Sex Ratio (♀:♂)	Eye* L (%)	Eye* R (%)	Females** SL (cm)	Females** WW (g)	Ovaries TL (cm)	Ovaries W (cm)	Ovaries WW (g)	Maturing Females (%)
1 1/19	30	19 (63)	11 (37)	2:1	50	50	39.3 (32.9-50.0)	1140 (652-1877)	10.4 (6.0-18.5)	4.6 (2.0-9.2)	24.20 (2.64-113.30)	32
2 2/12	40	28 (70)	12 (30)	2:1	45	55	35.6 (29.2-41.3)	1042 (549-1707)	13.0 (2.4-23.0)	5.6 (1.9-11.0)	48.8 (1.58-153.00)	67
3 4/25	16	4 (25)	16 (75)	1:3	87	13	35.0 (30.5-38.0)	1172 (710-1360)	7.9 (1.2-16.0)	3.1 (1.0-6.0)	15.7 (0.56-51.22)	25

Exp. No. Date	Liver Color--Both Sexes Yellow (%)	Liver Color--Both Sexes Red (%)	Males** SL (cm)	Males** WW (g)	Testes L (cm)	Testes W (cm)	Testes WW (g)	Ripe Males (%)
1 1/19	76	24	37.1 (32.1-44.1)	911 (686-1300)	4.0 (1.2-10.0)	1.5 (0.5-3.5)	2.54 (0.13-7.50)	38
2 2/12	67	33	32.4 (29.8-35.4)	707 (586-872)	4.5 (2.5-6.0)	2.0 (1.0-3.0)	4.03 (0.28-6.12)	75
3 4/25	100	0	32.9 (29.5-37.2)	915 (540-1270)	3.7 (1.7-6.5)	1.4 (0.5-2.0)	1.93 (0.14-6.53)	58

*Side of fish with most dorsad eye and the dorsal operculum; R = right, L = left.
**Values in parentheses are ranges; other values are means for that experiment.

SL = Standard Length; WW = Wet Weight; TL = Total Length.

Table 2. Experimental conditions. Starry flounder exposed during egg maturation prior to spawning (Experiments 1, 2) and after spawning (Experiment 3). Values in parentheses are ranges, other values are means.

Exp. No.	Dates Days Hrs.	Treatment	Fish No.	Fish Tot. WW (Kg)	Fish WW/L (g)	Mean Water* Concentration (mg/L (ppm)	Oxygen (ppm)	Temperature (°C)	Salinity (ppt)	Volume Water (Liters)	Flow Rate (L/Min)
1	1/18 to 1/23 5 120	Control	15	14.70	16.97	0	6.1 (5.0-8.6)	10.7 (9.5-11.7)	19.7 (19.0-21.0)	866	3 (1-3**)
		Exposed	15	17.57	20.29	0.140 (.041-.326)	5.8 (4.6-8.0)	Same	Same	Same	Same
2	2/12 to 2/19 7 168	Control	20	19.02	21.96	0	8.2 (7.0-8.7)	13.7 (12.5-14.5)	29.1 (29.0-30.0)	866	7 (3-7**)
		Exposed***	20	20.35	23.50	0.115 (0.45-.353)	7.9 (6.4-8.8)	Same	Same	Same	Same
3	4/25 to 5/15 21 504	Control	8	7.15	8.25	0	7.7 (6.1-8.8)	17.2 (15.8-18.5)	18.8 (16.5-19.5)	866	8
		Exposed	8	8.52	9.84	0.221 (.144-.265)	7.7 (6.4-8.6)	17.4 (15.9-18.8)	Same	Same	Same

*Water Concentration = total of 6 monocyclic aromatics in WSF (M-1); benzene, toluene, o-, m-, p-xylene, ethylbenzene. Cyclohexanes (CH), other monocyclics (M-2) and dicyclics (D) undetectable in water samples (<0.010 mg/L).

**Flow rate was too low; increased during first exposure day.
***Remaining fish fed after exposure for 1-wk depuration period.
WW = Wet Weight

Table 3. Procedure for analysis of low-boiling-point hydrocarbons in animal tissues. (Benville et al, MS in prep.)

1. Place 10 grams of tissue in a clean, glass culture tube (with a teflon-seal screw cap).
2. Add 6 ml of 4N NaOH and 4 ml of TF-Freon and cap tightly.
3. Place tube in oven (or water bath) for 18 hours at 30°C. Shake tube 4 or 5 times during this time.
4. Remove tube from oven and shake vigorously for one minute.
5. Centrifuge tube (while still warm) for 10 minutes at 3000 rpm.
6. If freon layer is clear (not cloudy), draw off with pipette and store in a clean, glass vial with a teflon-seal screw cap until ready to inject on GC.

Emulsions:

If the freon layer is clouded, use following procedure:

7. Freeze clouded sample and recentrifuge while still frozen (20-30 minutes at 2000-3000 rpm).
8. If sample is still cloudy, repeat.
9. If sample has not cleared, add 1-2 ml of 20% H_2SO_4, shake, and recentrifuge. A 15-20% reduction in recovery will result if it is necessary to follow this step.

RECOVERY RATE = 90-96% if tubes remain tightly capped.

LEVEL OF DETECTION = 0.025 μg/g wet weight.

Table 4. Summary of mean concentrations of monocyclic and dicyclic aromatic and cyclohexane components in gonads of immature and maturing starry flounder exposed to the WSF of Cook Inlet crude oil during gonadal maturation. Experiment 2. No immature males in samples. Percentages of total concentrations in parentheses. Tissue concentrations are in μg/g wet weight.
Total Accumulation = Total Mean Tissue Concentration (μg/g)/Mean Water Concentration (0.115 mg/L).

Treatment	Sex	Maturity	Tissue	No.	Mean M-1	Mean CH	Mean M-2	Mean D	Total Mean M-1+CH	Total Mean All	Total Accumulation M-1+CH	Total Accumulation All
Exposed	M	Mature (Ripe)	Testis	5	ND	ND	-	-	ND	-	ND	-
			Liver	4	5.891 (70)	2.559 (30)	-	-	8.450	-	73.5X	-
	F	Immature	Ovary	2	0.181 (20)	0.709 (80)	-	-	0.890	-	7.7X	-
			Liver	2	1.346 (100)	ND (0)	-	-	1.346	-	11.7X	-
	F	Mature	Ovary	6	4.801 (37)	3.784 (29)	2.228 (17)	2.163 (17)	(8.585)	12.976	74.6X	112.8X
			Liver	5	9.708 (63)	5.827 (37)	-	-	15.535	-	135.1X	-
Control	F	Immature	Ovary	1	ND	ND	-	-	ND	-	0	0
			Liver	1	ND	ND	-	-	ND	-	0	0
	F	Mature	Ovary	2	ND	ND	-	-	ND	-	0	0
			Liver	2	ND	ND	-	-	ND	-	0	0

M-1 = Monocyclics-1 = Benzene, toluene, ethylbenzene, p-xylene, o-xylene, m-xylene.
CH = Cyclohexanes = Methyl cyclohexane, Cis 1, 3 dimethyl cyclohexane, 1, 2 dimethyl cyclohexane, C_3 cyclohexane and 3 unidentified compounds, also probably cyclohexanes.
M-2 = Monocyclics-2 = Isopropyl benzene, n-propyl benzene, total C_3 benzenes, total C_4 benzenes and total C_5 benzenes.
D = Dicyclics = Naphthalene, 2-methyl naphthalene, 1-methyl naphthalene, total C_2-naphthalenes.
*Monocyclics-2 (M-2) and dicyclics (D) measured only in mature ovaries.

Table 5. Summary of results from histological examination of ovaries of adult flounder exposed to the WSF of Cook Inlet crude oil prior to spawning. Experiment 1.

Day Date	Treatment	Mean WSF-M-1 Concen. (mg/L)	Maturity[1]	L (cm)	WW (g)	GSI[2]	Mat. Stage (1-11)[3]	Description	Mean Max Diam. (μ)	% Abn.	% Dead
0.25 1/19	Cont.	ND	Imm.	8.5	6.2	0.58	3	Perinucleolus	120	0	0
	Exp.	0.118	Imm.	7.0	5.2	0.48	3	Perinucleolus	100	0	0
	Exp.		Imm.	7.0	3.8	0.55	3	Perinucleolus	120	0	0
1 1/20	Cont.	ND	Mat.	12.0	27.7	2.26	4 to 5	Yolk Vesicle to Primary Yolk	130 to 280	0	0
	Exp.	0.090	Mat.	10.0	17.1	1.43	4	Yolk Vesicle	260	0	0
2 1/21	Cont.	ND	Imm.	6.2	4.1	0.42	3	Perinucleolus	100	0	0
	Exp.[4]	0.098	Mat.	18.0	91.9	5.40	6	Secondary Yolk	460	3	5
3 1/22	Cont.	ND	Mat.	8.0	8.0	0.73	4	Yolk Vesicle	200	0	0
	Exp.	0.224	Mat.	18.5	113.3	6.04	6	Secondary Yolk	410	5	5
	Exp.		Imm.	5.2	2.6	0.35	3	Perinucleolus	120	21	12
4 1/23	Cont.	ND	Imm.	10.0	6.0	0.62	3	Perinucleolus	100	0	0
	Exp.	0.226	Imm.	7.0	4.4	0.36	3	Perinucleolus	100	32	10
	Exp.		Mat.	14.5	47.2	3.00	4 to 5	Yolk Vesicle to Primary Yolk	150 to 310	4	13

[1]Mat. = Early maturation stages.
Imm. = Not maturing as yet, although adults.

[2]GSI = Gonadosomatic Index = Ovary Wet Weight X 100/Body Wet Weight.

[3]Stages from Yamamoto, 1956.

[4]Total monocyclics (M-1) = 6.470 μg/g (wet weight).

Table 6. Summary of results from histological examination of ovaries of adult flounder exposed to the WSF of Cook Inlet crude oil prior to spawning. Experiment 2.

Day Date	Treat-ment	WSF-MA-1 Concen. (mg/L)	Tissue Concentrations (µg/g)[1] M-1	CH	M-2	D	Total M1+CH	All	Accumulation M1+CH	All	Matu-rity	Ovary L (cm)	WW (g)	GSI[2]	Mat.[3] Stage (1-11)	Description	Mean Max Diam. (µ)	% Abn.	% Dead
0.25	Cont.	0	ND	ND	-	-	ND	-	ND	-	Imm.	2.8	0.70	0.07	3	Perinucleolus	100	0	0
2/12	Exp.	0.182	0.363	0.187	-	-	0.550	-	3X	-	Imm.	7.0	4.29	0.46	3	Perinucleolus	100	0	0
1	Cont.	0	ND	ND	ND	ND	ND	ND	0	0	Mat.	21.2	110.0	7.62	6	Secondary Yolk	560	0	0
2/13	Exp.	0.123	4.652	3.646	-	-	8.298	-	67X	-	Mat.	19.0	99.0	7.26	7	Tertiary Yolk	670	0	0
	Exp.	0.123	3.506	2.996	1.977	1.903	6.502	10.382	53X	84X	Mat.	12.5	39.5	3.66	6	Secondary Yolk	460	0	0
2	Cont.	0	ND	ND	-	-	ND	-	0	-	Imm.	7.1	3.33	0.35	3	Perinucleolus	120	0	0
2/14	Exp.	0.119	ND	1.232	-	-	1.232	-	10X	-	Imm.	7.0	3.94	0.51	3	Perinucleolus	120	1	10
3	Cont.	0	ND	ND	-	-	ND	-	0	-	Mat.	23.0	129.0	7.66	6	Secondary Yolk	560	0	0
2/15	Cont.	0	ND	ND	-	-	ND	-	0	-	Mat.	22.0	97.0	8.52	6	Secondary Yolk	560	0	0
	Exp.	0.088	4.877	3.048	2.277	2.138	7.925	12.340	90X	140X	Mat.	20.0	150.0	8.79	7	Tertiary Yolk	670	15	12
4	Cont.	0	ND	ND	-	-	ND	-	0	-	Imm.	5.5	3.50	0.48	3	Perinucleolus	120	0	0
2/16	Cont.	0	ND	ND	-	-	ND	-	0	-	Mat.	14.5	45.0	3.70	6	Secondary Yolk	460	0	0
	Exp.	0.104	5.720	4.528	2.336	2.034	10.248	14.618	98X	140X	Mat.	18.0	82.0	5.37	6	Secondary Yolk	560	28	20
5	Cont.	0	ND	ND	-	-	ND	-	0	-	Mat.	11.5	43.0	4.20	6	Secondary Yolk	460	0	0
2/17	Exp.	0.112	5.043	3.609	2.390	2.327	8.652	13.369	77X	119X	Mat.	21.5	141.0	10.23	7	Tertiary Yolk	670	20	33
	Exp.	0.112	4.136	3.023	-	-	7.159	-	64X	-	Mat.	14.0	43.0	5.26	6	Secondary Yolk	460	5	8
6	Cont.	0	ND	ND	-	-	ND	-	0	-	Mat.	17.0	80.0	6.58	6	Secondary Yolk	510	0	0
2/18	Cont.	0	ND	ND	-	-	ND	-	0	-	Mat.	13.5	34.0	3.12	6	Secondary Yolk	410	0	2
	Exp.	0.075	11.871	(M-1+CH)	-	-	11.871	-	158X	-	Mat.	17.5	66.0	5.40	6	Secondary Yolk	510	32	25
	Exp.	0.075	4.396	3.606	2.009	2.554	8.002	12.565	107X	167X	Mat.	14.0	56.0	5.73	6	Secondary Yolk	460	8	0
7	Cont.	0	ND	ND	ND	ND	ND	ND	0	0	Mat.	15.0	40.0	3.70	6	Secondary Yolk	460	0	0
2/19	Exp.	0.075	5.262	4.918	2.378	2.023	10.180	14.581	136X	194X	Mat.	17.0	63.0	7.63	8	Migratory Nucl.	670	10	28

[1]Tissue concentrations of other monocyclics (M2) and dicyclics measured only in mature ovaries. Mean concentrations in Table 4.

[2]GSI = Gonadosomatic Index = Ovary Wet Weight X 100/Body Wet Weight.

[3]Stages from Yamamoto, 1956.

Table 7. Means of ovarian and egg parameters showing acceleration of maturation in ovaries of exposed flounder. Mature females equally represented in control and exposed samples. Experiment 2.

			Ovaries			Eggs					
						Predominant Maturation Stage				Percentage	
Treatment	No. Fem. (n)	Maturity	Length (cm)	Wet Wt. (g)	GSI[1]	Stage No.	Ovaries (n)	Description	Max. Diam. (μ)	Abnormal (%)	Dead (%)
Control	3	Immature	5.1	2.5	0.30	3	3	Perinucleolus	110	0	0
Exposed	2	Immature	7.0	4.1	0.48	3	2	Perinucleolus	110	0.5	0.2
Control	8	Maturing	17.2	72.3	5.64	6	8	Secondary Yolk only	497 (410-460)	0	0
Exposed	9	Maturing	17.0	82.2	6.59	6.6 (6-8)	5	Secondary Yolk	570 (410-670)	13.0	15.0
							3	Tertiary Yolk			
							1	Migratory Nucleus			

[1]GSI = Gonadosomatic Index = Ovary Wet Weight X 100/Body Wet Weight.

Table 8. Summary of effects observed in immature and mature starry flounder exposed to approximately 100 ppb of the WSF of Cook Inlet crude oil for 7 days. Effects marked with asterisk also observed in flounder after 7 days of depuration. A (+) indicates an elevation of effect above controls; a (-) indicates a reduction of effect below controls. Other effects not observed in controls.

	Behavior-Adult		Liver		Gonads				
Stage-Sex	Activity	VR	Total Accum.[1]	Tissue Effects	Total Accum.[1]	Water Uptake	GSI	Gonad-Gametes Effects	Gametogenesis
Mature Male	+	+	73X	+Vacuolization* +Lipid deposition* +Disruption of hepatic muralia +Sinusoidal congestion	ND	+	+	None Obvious	+Spermiation
Immature Female	+	+	12X	As above	8X	+	+	Pale color Erythrocyte Destruction Vacuolization (0.5-13.2%)* +Nuclear disintegration* +Atresia or egg death (0.2-5.5%)*	-Oocytes-atresia*
Maturing Female	+	+	135X	As above	75X	+	+	Vacuolization (3-13%) +Thicker zona radiata Egg death (5.8-15.0%)	+Egg size +Maturation rate +Vitellinogenesis
Adult Female-Resting stage (Yocom et al., manuscript)	NM	NM	2800X	NM	7X (Toluene only)	NM	NM	----------------	----------------

[1]Total Accumulation = Mean Tissue Concentration of Monocyclics (M-1) and Cyclohexanes (CH)/Mean Water Concentration of M-1 and CH.

ND = Not detectable; NM = Not measured; GSI = Gonadosomatic Index.

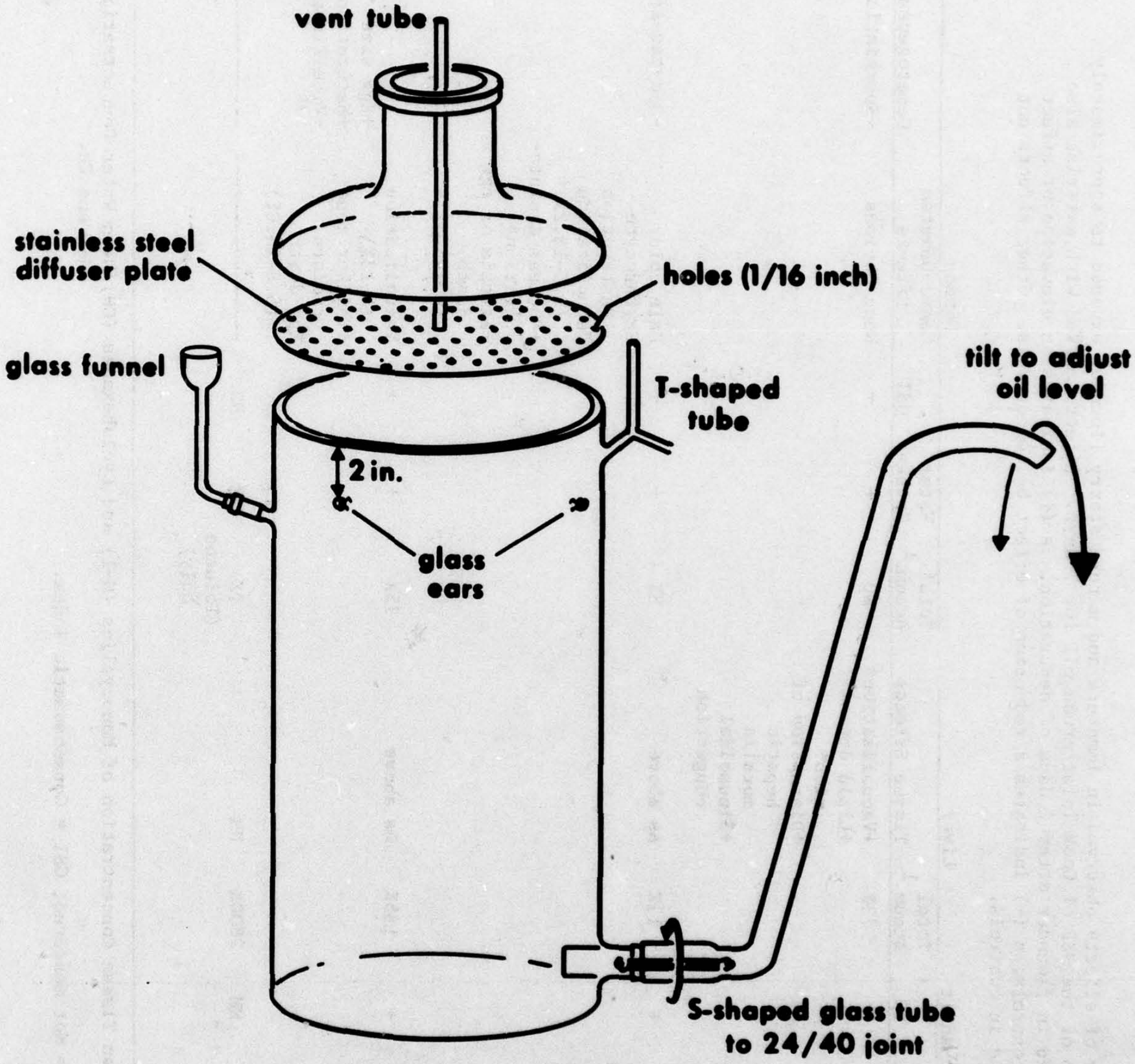

Figure 1. Apparatus (solubilizer) for continuously dosing flounder with the water-soluble fractions (WSF) of crude oil (from Benville et al., manuscript in preparation).

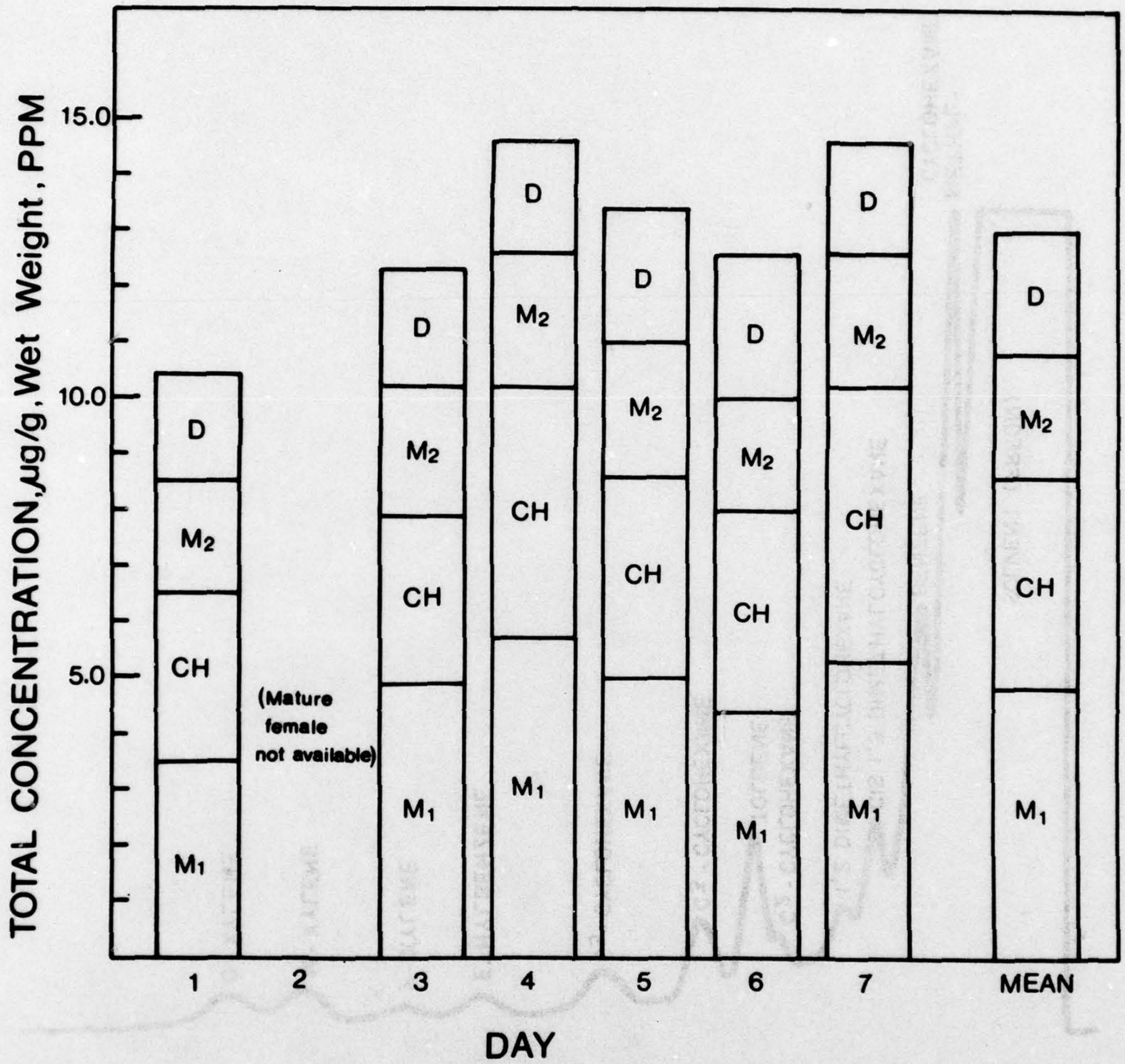

Figure 2. Concentrations of aromatics and alkyl cyclohexanes in maturing ovaries of starry flounder. M1 = Monocyclics 1; CH = Cyclohexanes; M2 = Monocyclics 2; D = Dicyclics. Mean: M1 = 37%; CH = 29%; M2 = 17%; D = 17%.

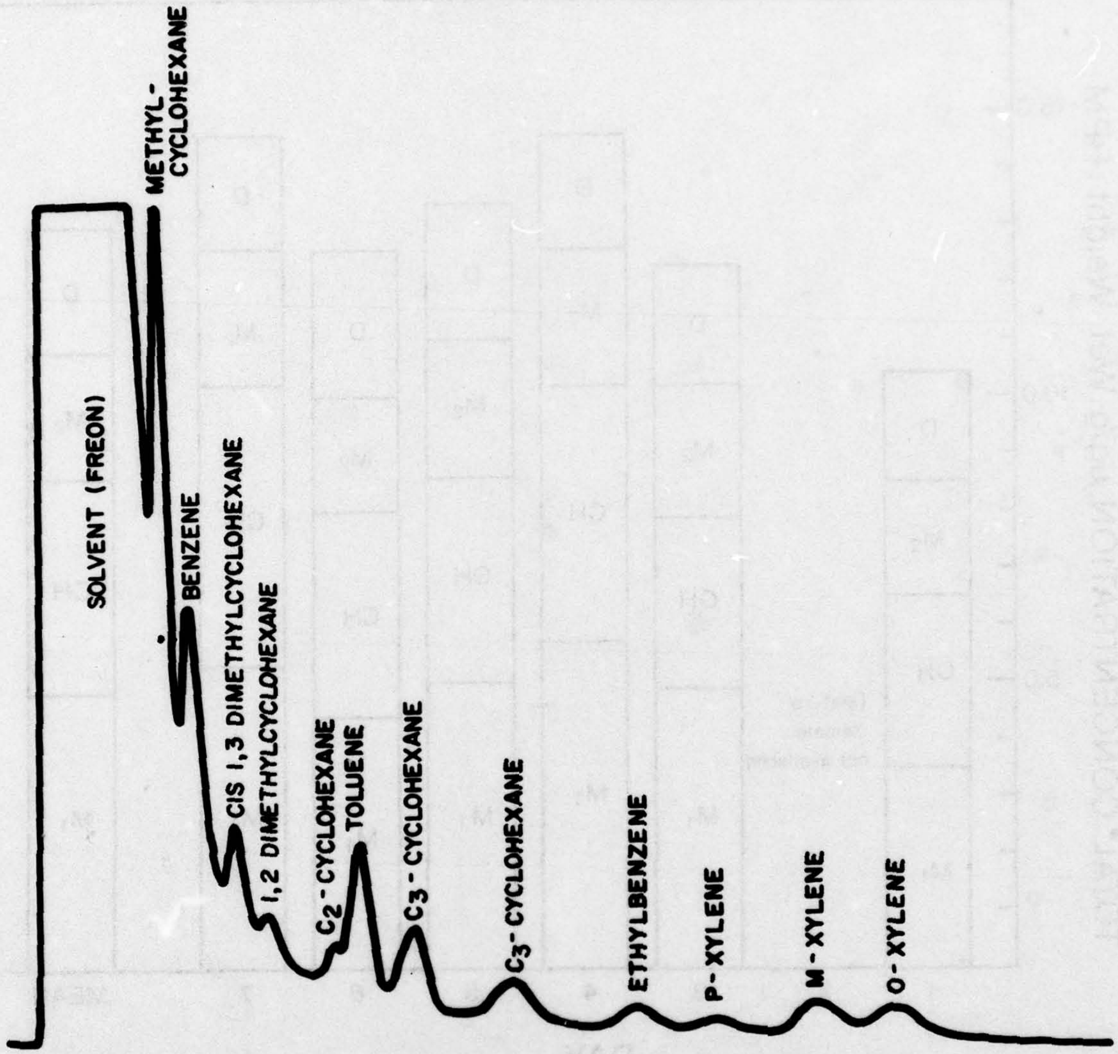

Figure 3. Chromatogram of low-boiling-point hydrocarbons detected in a maturing ovary of a starry flounder exposed to 115 ppb WSF in the water column for 7 days. Total concentration = 8.43 μg/g (ppm).

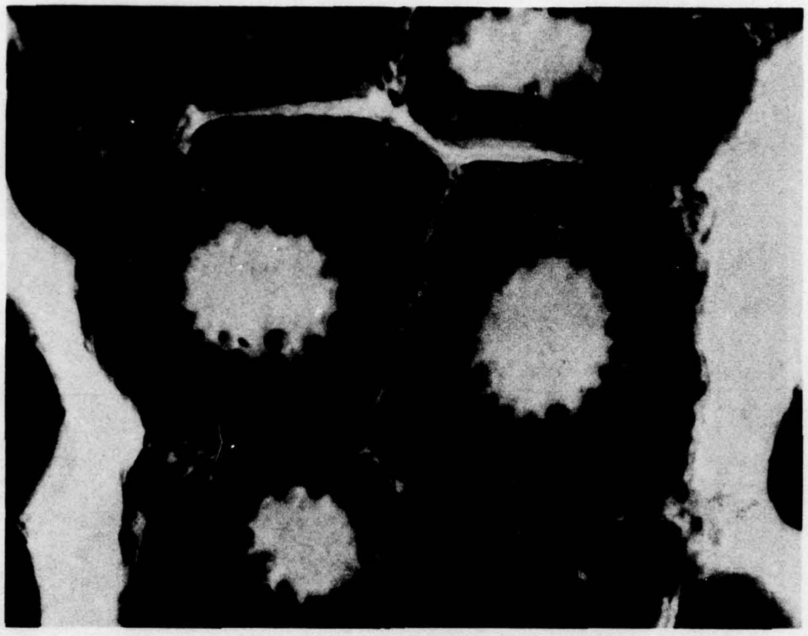

Figure 4A Photomicrograph of normal immature eggs (perinucleolus) stage in control flounder. 400 X.

Figure 4B Photomicrograph of abnormal immature eggs (perinucleolus stage) in exposed flounder. Eggs have cytoplasmic vacuoles. 400 X.

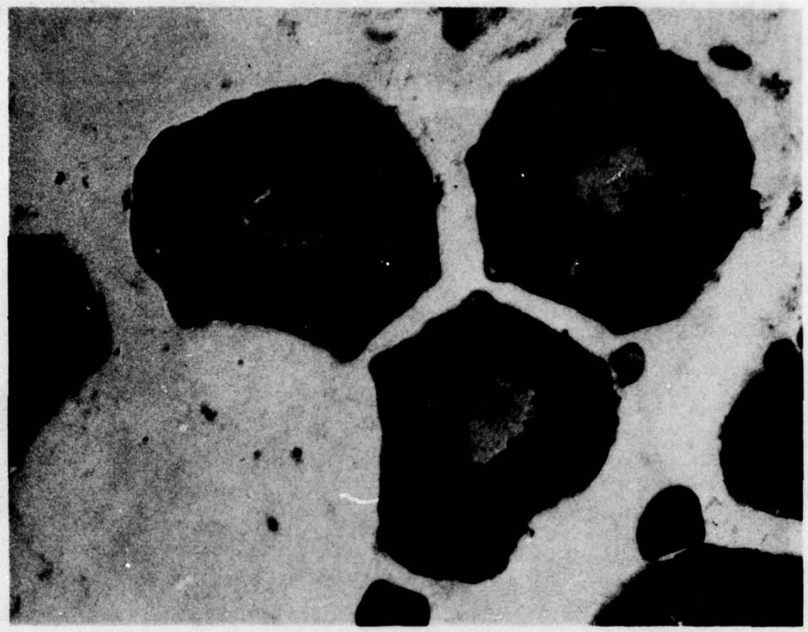

Figure 5A Photomicrograph of normal mature eggs (secondary yolk stage) in control flounder. 100 X.

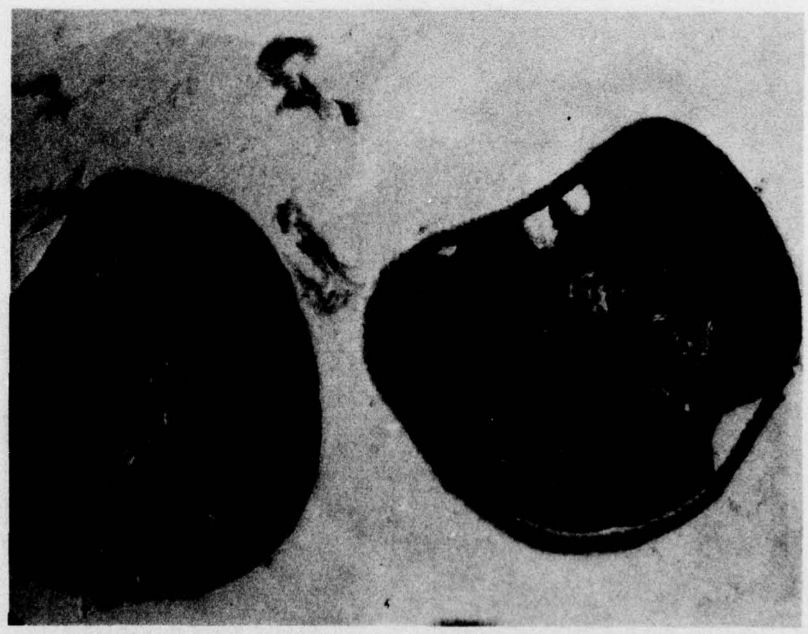

Figure 5B Photomicrograph of abnormal mature eggs (tertiary yolk stage) in exposed flounder. Eggs have cytoplasmic vacuoles. 100 X.

Figure 6A Photomicrograph of abnormal mature egg (tertiary yolk stage) in exposed flounder. Cytoplasmic vacuole in periphery of egg between cytoplasm and zona radiata. 400 X.

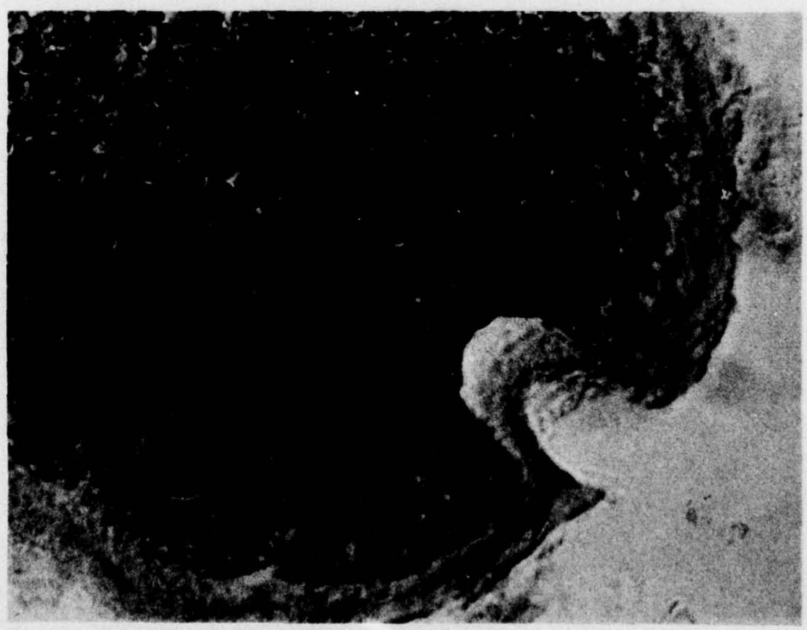

Figure 6B Photomicrograph of abnormal mature egg (tertiary yolk stage) in exposed flounder. Cytoplasmic vacuole in periphery of egg extruding through zona radiata. 400 X.

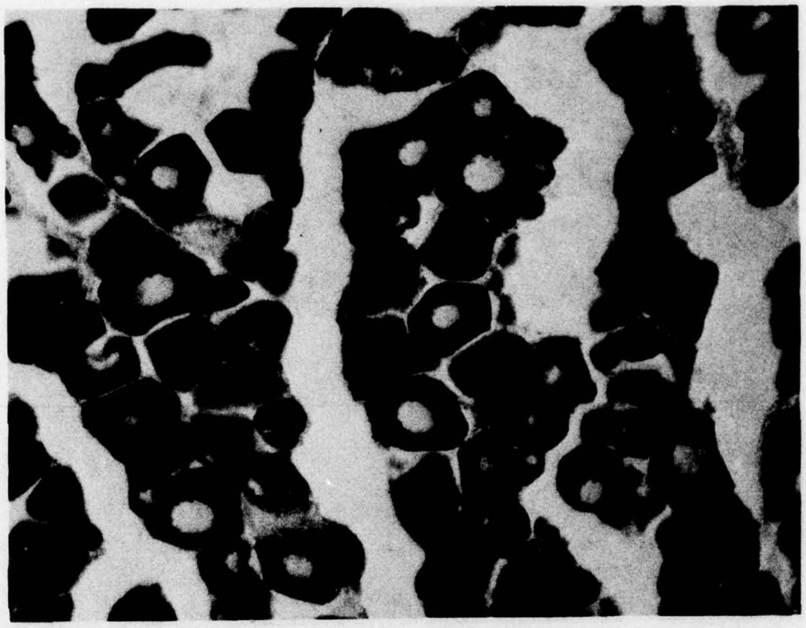

Figure 7A Photomicrograph of normal immature eggs (perinucleolus stage) in control flounder. Note compact groups of many eggs. 100 X.

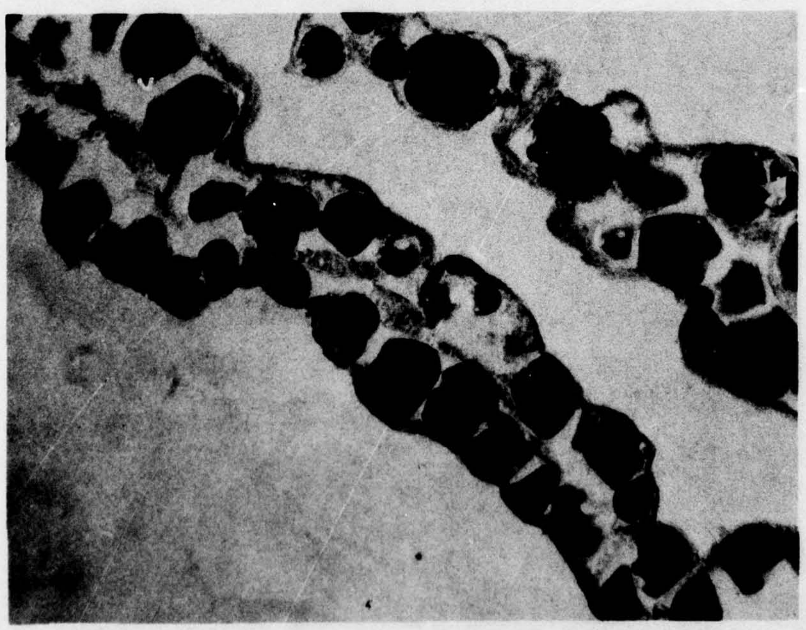

Figure 7B Photomicrograph of immature eggs in perinucleolus stage in exposed flounder. Note relatively small numbers of eggs compared to control. 100 X.

Figure 8A Photomicrograph of dying immature egg (possibly atresic) in exposed flounder. Nucleoplasm starting to coalesce into droplets. 400 X.

Figure 8B Photomicrograph of dying immature egg (possibly atresic) in exposed flounder. Nucleoplasm coalesced into single droplet, nuclear and cell membranes disintegrated. 400 X.

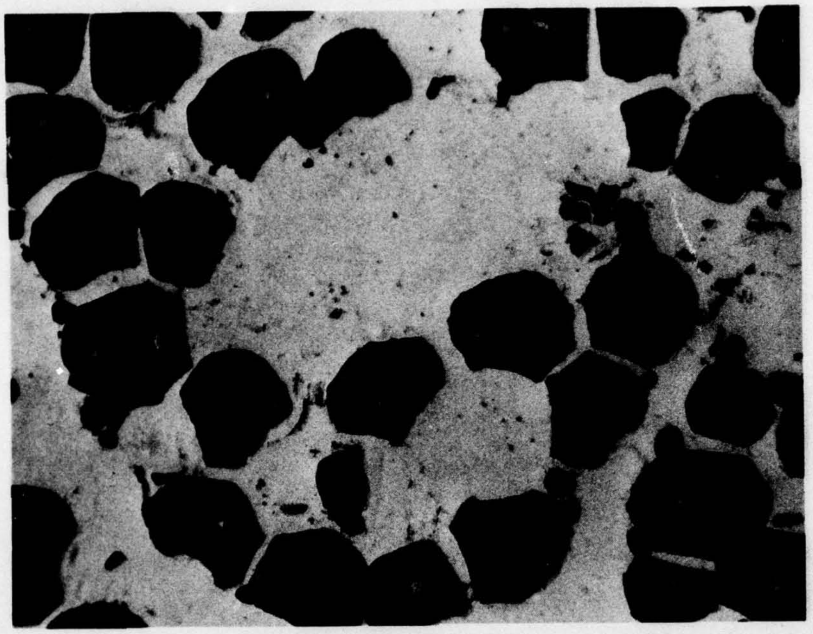

Figure 9A Photomicrograph of normal mature eggs (secondary yolk stage) in control flounder. 40 X.

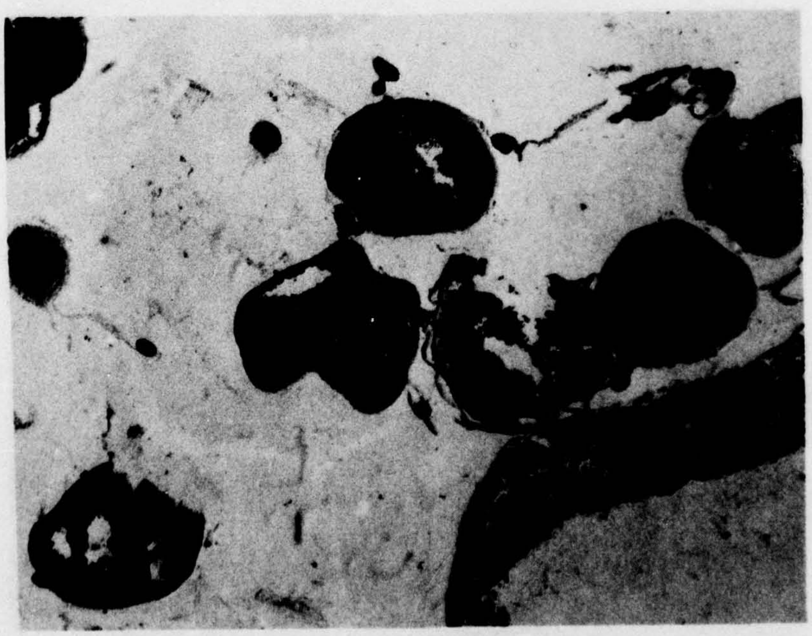

Figure 9B Photomicrograph of dying mature eggs (tertiary yolk stage) in exposed flounder. Note necrosis of eggs, thickened zona radiata. 40 X.

Figure 10A Section of liver tissue from control flounder. 40 X.

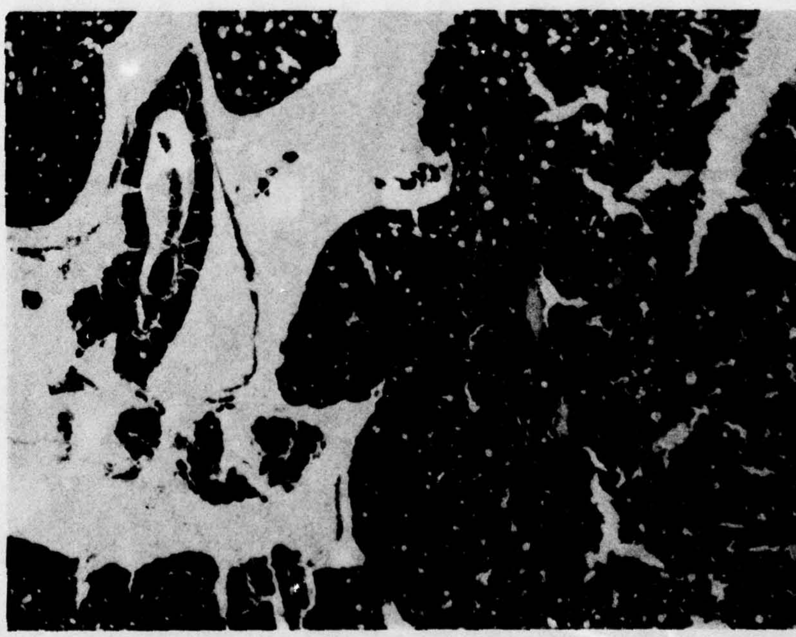

Figure 10B Section of liver tissue from exposed flounder showing heavy vacuolization. 40 X.

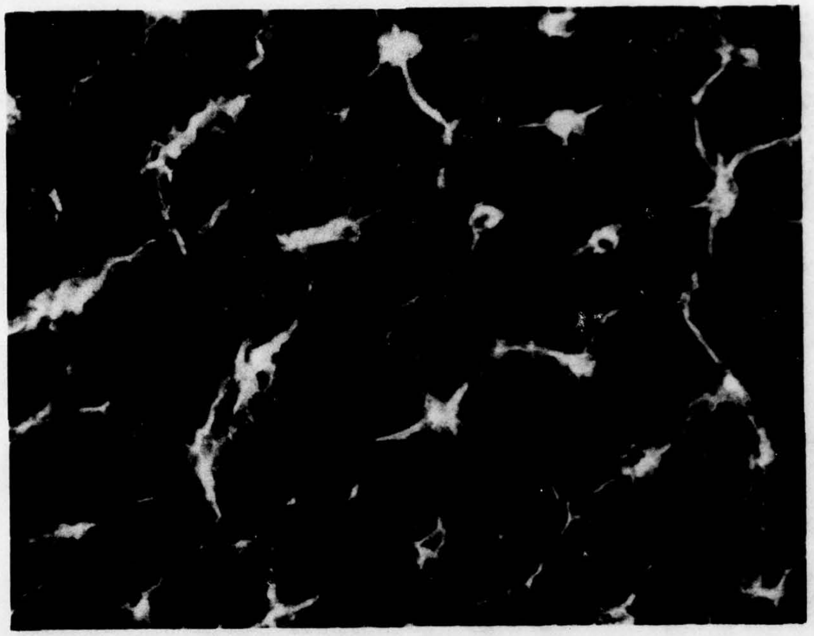

Figure 11A Cross section of hepatic muralia in liver of control flounder showing well-organized hepatocytes surrounding central sinusoids. 400 X.

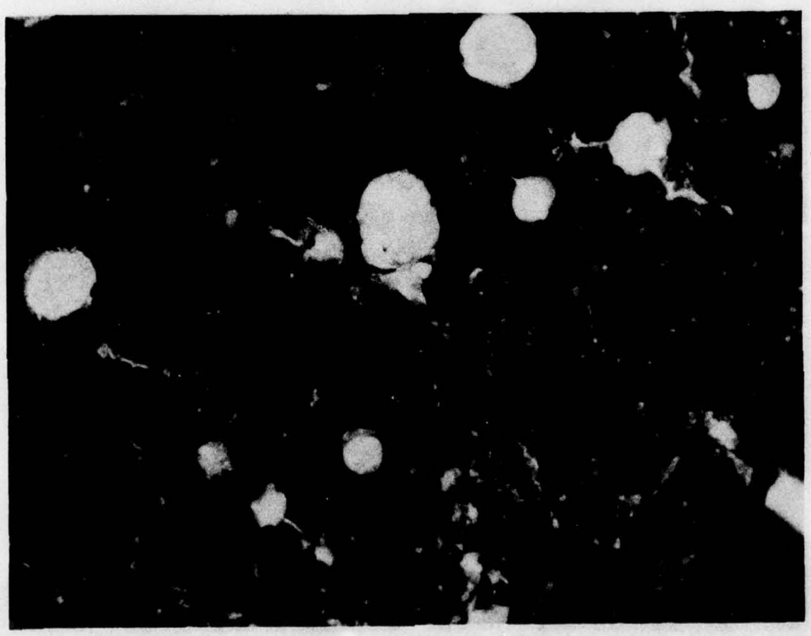

Figure 11B Cross section of hepatic muralia from liver of exposed flounder showing lack of definite structure in muralia and numerous vacuoles. 400 X.

APPENDIX

Table A. Concentrations of monocyclic aromatic components in tissues of starry flounder exposed to the WSF of Cook Inlet crude oil prior to spawning. Experiment 2. Monocyclics not detectable (<0.010 μg/g) in control flounder.

Concentration (ppm) - μg/g (wet weight)
Monocyclics 1 - (M-1)

Treatment Sample	Time (Day-Date-Hrs)	Tissue	Stage	Benzene	Toluene	Ethyl-Benzene	P-Xylene	M-Xylene	O-Xylene	Total Mono-cyclics	Total* Accumu-lation
Seawater	0-1			0.090	0.074	0.005	ND	0.007	0.006	0.182	-
Exposed #1 F	2/12	Ovary	Im-mature	0.309	ND	0.011	0.043	ND	ND	0.363	2.0X
	6	Liver		0.563	1.353	ND	ND	0.495	ND	2.411	13.2X
Exposed #2 M		Testis	Ripe	ND	ND	ND	ND	ND	ND	ND	None
		Liver		0.366	1.024	ND	ND	0.390	ND	1.780	9.8X
Seawater	1			0.046	0.060	0.004	ND	0.007	0.006	0.123	-
Exposed #1 F	2/13	Ovary	Mature	NM	2.734	0.426	ND	0.780	0.712	4.652	37.8X
	24	Liver		0.253	0.852	0.306	ND	0.502	ND	1.913	15.5X
Exposed #2 F		Ovary	Mature	1.633	1.873	ND	ND	ND	ND	3.506	28.5X

ND = Not detectable, but may be present.
NM = Not measured.
M = Male.
F = Female.
Mature = Maturing, but not running ripe.
Immature = Not maturing for spawning in this year.
Ripe = Males with running ripe sperm.

*Total Accumulation = Tissue Concentration (μg/g)/Water Concentration (mg/L).

Appendix - Table A (Contd)

Treatment Sample	Time (Day-Date-Hrs)	Tissue	Stage	Benzene	Toluene	Ethyl-Benzene	P-Xylene	M-Xylene	O-Xylene	Total Mono-cyclics	Total* Accumu-lation
Seawater	2			0.045	0.059	0.004	ND	0.006	0.005	0.119	-
Exposed #1 M	2/14	Testis	Ripe	ND	ND	ND	ND	ND	ND	ND	None
	48	Liver		ND	0.291	ND	ND	ND	ND	0.291	2.4X
		GB		ND	0.461	ND	ND	ND	ND	0.461	3.9X
Exposed #2 F	2/14	Ovary	Im-mature	ND	ND	ND	ND	ND	ND	ND	None
	48	Liver		ND	0.281	ND	ND	ND	ND	0.281	2.4X
		GB		ND	0.469	ND	ND	ND	ND	0.469	3.9X
Seawater	3			0.032	0.048	ND	ND	0.005	0.003	0.088	-
Exposed #1 F		Ovary	Mature	1.269	2.284	0.385	ND	0.370	0.569	4.877	55.4X
	2/15	Liver		2.820	8.334	1.740	0.726	3.922	3.262	20.804	236.4X
Exposed #2 M	72	Testis	Ripe	ND	ND	ND	ND	ND	ND	ND	None
		Liver		ND	0.524	ND	ND	ND	ND	0.524	5.9X
		GB		ND	0.442	ND	ND	ND	ND	0.442	5.0X

Appendix - Table A (Contd)

Treatment Sample	Time (Day-Date-Hrs)	Tissue	Stage	Benzene	Toluene	Ethyl-Benzene	P-Xylene	M-Xylene	O-Xylene	Total Mono-cyclics	Total* Accumu-lation
Seawater	4			0.041	0.053	0.004	ND	0.006	ND	0.104	-
Exposed #1 F	2/16	Ovary	Mature	1.554	2.846	0.400	ND	0.851	0.069	5.720	55.0X
	96	Liver		0.075	1.966	ND	ND	0.879	ND	2.920	28.1X
		GB		ND	ND	ND	ND	ND	ND	ND	None
Exposed #2 M		Testis	Ripe	ND	0.010	ND	ND	ND	ND	0.010	0.1X
		Liver		1.916	6.783	1.449	0.640	3.977	3.264	18.029	173.4X
		GB		ND	0.306	ND	ND	ND	ND	0.306	2.9X
Seawater	5			0.046	0.057	0.004	ND	0.005	ND	0.112	-
Exposed #1 F	2/17	Ovary	Mature	1.539	2.898	ND	ND	0.612	ND	5.043	45.0X
	120	Liver		0.724	1.709	0.404	ND	0.720	ND	3.557	31.8X
		GB		ND	0.348	ND	ND	ND	ND	0.348	3.1X
Exposed #2 F		Ovary	Mature	1.378	2.495	ND	ND	0.255	0.008	4.136	36.9X
		Liver		2.466	7.112	1.603	0.688	4.188	3.233	19.290	172.2X
		GB		ND	0.280	ND	ND	ND	ND	0.280	2.5X

Appendix - Table A (Contd)

Treatment Sample	Time (Day-Date-Hrs)	Tissue	Stage	Benzene	Toluene	Ethyl-Benzene	P-Xylene	M-Xylene	O-Xylene	Total Mono-cyclics	Total* Accumu-lation
Seawater	6			0.026	0.044	ND	ND	0.005	ND	0.075	-
Exposed #1 F	2/18	Ovary	Mature	NM	4.509	4.356	0.666	1.206	1.134	11.871	158.3X
Exposed #2 F		Ovary	Mature	1.254	2.290	ND	0.007	0.845	ND	4.396	58.6X
Exposed #1 F	2/19	Ovary	Mature	1.038	2.916	0.518	0.050	0.513	0.227	5.262	70.2X
Exposed #2 M		Testis	Ripe	ND	ND	ND	ND	ND	ND	ND	None
		Liver		0.995	1.974	0.594	ND	2.790	2.476	8.829	117.7X
Mean Seawater Concentrations (mg/L) (Percentages)				0.047 (41%)	0.056 (49%)	0.003 (3%)	ND (0%)	0.006 (5%)	0.003 (3%)	0.115	

APPENDIX

Table B. Concentrations of cyclohexane components in tissues of starry flounder exposed to the WSF of Cook Inlet crude oil prior to spawning. Experiment 2. Cyclohexanes and unidentified components not detectable in water column samples or control flounder.

Concentration (ppm) - μg/g (wet weight)
Cyclohexanes - (CH)

Treatment Sample	Time Day Date Hrs.	Tissue	Stage	Methyl Cyclo-hexane	Cis 1, 3 Dimethyl Cyclo-hexane	1, 2 Dimethyl Cyclo-hexane	Uniden-tified #1	Uniden-tified #2	C_3 Cyclo-hexane	Uniden-tified #3	Total Cyclo-hexanes	Maximum* Total Accumu-lation
Exposed #1 F	0-1 2/12 6	Ovary	Im-mature	ND	ND	ND	0.181	0.006	ND	ND	0.187	37X
		Liver		ND	ND	ND	ND	ND	ND	ND	ND	None
Exposed #2 M	0-1 2/12 6	Testis	Ripe	ND	ND	ND	ND	ND	ND	ND	ND	None
		Liver		ND	ND	ND	ND	ND	ND	ND	ND	None
Exposed #2 F	1 2/13 24	Ovary	Mature	1.918	ND	ND	1.078	ND	ND	ND	2.996	599X
		Liver		0.447	0.121	ND	ND	ND	ND	ND	0.568	114X
Exposed #1 M	2 2/14 48	Testis	Ripe	ND	ND	ND	ND	ND	ND	ND	ND	None
		Liver		ND	ND	ND	ND	ND	ND	ND	ND	None
Exposed #2 F	2 2/14 48	Ovary	Im-mature	ND	ND	ND	1.213	ND	.019	ND	1.232	246X
		Liver		ND	ND	ND	ND	ND	ND	ND	ND	None

ND = Not detectable, but may be present; M = Male; F = Female; Mature = Maturing, but not running ripe; Immature = Not maturing for spawning in this year; Ripe = Males with running ripe sperm.

*Total Accumulation = Tissue Concentration (μg/g)/Water Concentration (mg/L).
Water Concentration less than 0.010 mg/L, not detectable; estimated as 0.005 mg/L total cyclohexanes.

Appendix - Table B (Contd)

Treatment Sample	Time Day Date Hrs.	Tissue	Stage	Methyl Cyclo-hexane	Cis 1, 3 Dimethyl Cyclo-hexane	1, 2 Dimethyl Cyclo-hexane	Uniden-tified #1	Uniden-tified #2	C_3 Cyclo-hexane	Uniden-tified #3	Total Cyclo-hexanes	Maximum* Total Accumu-lation
Exposed #1 F	3 2/15 72	Ovary	Mature, not measured.									
		Liver		9.575	1.464	0.044	1.968	0.009	ND	ND	13.060	2612X
Exposed #2 M	3 2/15 72	Testis	Ripe	ND	ND	ND	ND	ND	ND	ND	ND	None
		Liver		ND	ND	ND	ND	ND	ND	ND	ND	None
Exposed #1 F	4 2/16 96	Ovary	Mature	3.255	0.603	0.287	0.383	ND	ND	ND	4.528	906X
		Liver		1.977	0.521	0.248	ND	ND	ND	ND	2.746	549X
Exposed #2 M	4 2/16 96	Testis	Ripe	ND	ND	ND	ND	ND	ND	ND	ND	None
		Liver		5.118	1.175	0.590	ND	ND	ND	ND	6.883	1377X
Exposed #1 F	5 2/17 120	Ovary	Mature	2.893	0.544	0.172	ND	ND	ND	ND	3.609	722X
		Liver		1.689	0.386	0.223	ND	ND	ND	ND	2.298	460X
Exposed #2 F	5 2/17 120	Ovary	Mature	2.446	0.419	0.158	ND	ND	ND	ND	3.023	605X
		Liver		8.286	1.727	0.671	ND	ND	ND	ND	10.684	2137X

Appendix - Table B (Contd)

Treatment Sample	Time Day Date Hrs.	Tissue	Stage	Methyl Cyclo-hexane	Cis 1, 3 Dimethyl Cyclo-hexane	1, 2 Dimethyl Cyclo-hexane	Uniden-tified #1	Uniden-tified #2	C_3 Cyclo-hexane	Uniden-tified #3	Total Cyclo-hexanes	Maximum* Total Accumu-lation
Exposed #2 F	6 2/18 144	Ovary	Mature	2.778	0.580	0.248	ND	ND	ND	ND	3.606	721X
Exposed #1 F	7 2/19 168	Ovary	Mature	2.286	0.526	0.134	1.928	ND	0.029	.015	4.918	984X
Exposed #2 M	7 2/19 168	Testis	Ripe	ND	ND	ND	ND	ND	ND	ND	ND	ND
		Liver		2.128	1.160	0.065	ND	ND	ND	ND	3.353	671X

APPENDIX

Table C. Concentrations of monocyclic and dicyclic aromatic components in mature ovaries of starry flounder exposed to WSF of Cook Inlet crude oil prior to gonadal maturation. Experiment 2. Monocyclics-2 (M-2) and dicyclics not detectable in water column samples.

Concentration (ppm) - μg/g (wet weight)[1]
Monocyclics 2 - (M-2) and Dicyclics (D)

Treatment Sample	Time Date-Day	Iso-propyl-benzene	n-propyl-benzene	Total C_3-benzenes	Total C_4-benzenes	Total[2] mono-cyclics	Naphtha-lene	2-methyl-naphtha-lene	1-methyl-naphtha-lene	Total C_2-naphtha-lenes	Total di-cyclics	Total M-2+D	Maximum[3] Total Accumu-lation
Control 1 Female	2/13 1	ND	ND	ND	ND	ND	Contami-nated	ND	ND	ND	ND	ND	None
Exposed 2 Female	2/13 1	0.109	0.138	1.307	0.423	1.977	0.691	0.813	0.272	0.127	1.903	3.880	228X
Exposed 1 Female	2/15 3	0.118	0.163	1.426	0.570	2.277	0.890	0.499	0.428	0.321	2.138	4.415	260X
Exposed 1 Female	2/16 4	0.119	0.149	1.390	0.678	2.336	0.746	0.576	0.407	0.305	2.034	4.370	257X
Exposed 1 Female	2/17 5	0.143	0.182	1.050	1.015	2.390	1.176	0.455	0.455	0.241	2.327	4.717	277X
Exposed 1 Female	2/18 6	0.116	0.155	1.222	0.516	2.009	0.788	0.679	0.489	0.598	2.554	4.563	268X
Exposed 1 Female	2/19 7	0.118	0.152	1.406	0.702	2.378	0.776	0.592	0.407	0.248	2.023	4.401	259X
Control 1 Female	2/19 7	ND	ND	.002	0.013	0.015	ND	ND	ND	ND	ND	0.015	None

[1]Data converted from dry weight to wet weight on basis of % dry weight of total wet weight (analysis by Seattle Analytical Laboratory).

[2]Other monocyclics in Appendix Table A.

[3]Total Accumulation = Tissue Concentration (μg/g)/Water Concentration (mg/L).
Water Concentration less than 0.00025 mg/L, not detectable; estimated as 0.017 mg/L total monocyclics (M-2) and dicyclics (D).

APPENDIX

Table D. Concentration of monocyclic aromatic components in tissues of starry flounder after exposing to the WSF of Cook Inlet crude oil for 3 weeks; post-spawning period. Experiment 3. Monocyclics not detectable (<0.010 μg/g) in control flounder. Some samples pooled.

Concentration (ppm)-μg/g (wet weight)
Monocyclics-1 - (M-1)

Sample	Tissue	Stage	Benzene	Toluene	Ethyl-Benzene	P-Xylene	M-Xylene	O-Xylene	Total Mono-cyclics	Total* accumu-lation
1 Female	Ovary	Immature	ND	0.169	ND	ND	ND	ND	0.169	1.9X T
	Liver		5.011	16.272	10.435	1.283	7.057	5.524	45.582	206X
2 Male	Testis	Ripe	ND	0.352	ND	ND	ND	ND	0.352	4X T
	Liver		8.843	20.030	8.311	5.152	10.807	10.262	63.405	287X
4 Female	Ovary	Immature	ND	0.250	ND	ND	ND	ND	0.250	2.8X T
	Liver		4.049	12.332	2.731	0.939	5.869	4.641	30.561	138X
9 Male + 10 Male	Testis	Ripe	ND	0.313	ND	ND	ND	ND	0.313	3.6X T
9 Male	Liver		8.714	18.099	5.522	2.002	9.418	7.295	51.05	231X
10 Male	Liver		8.254	17.814	5.311	2.127	9.175	7.147	49.828	225X
3 Male + 11 Male	Testis	Ripe	0.359	1.002	ND	ND	ND	ND	1.361	6.2X
11 Male	Liver		15.444	30.016	8.157	2.793	12.404	9.876	78.69	356X
12 Female	Ovary	Immature	ND	0.716	ND	ND	ND	ND	0.716	8.1X T
	Liver		16.349	30.059	11.171	5.644	13.185	12.029	88.437	400X
Mean Seawater Concentration (mg/L)			0.133	0.088	ND	ND	.0003	ND	0.221	

ND = Not detectable but may be present; Immature = Ovaries in resting stage; T = Accumulation of toluene only.

*Total Accumulation = Tissue Concentration (μg/g)/Mean Water Concentration (mg/L).

APPENDIX

Table E. Concentration of cyclohexane components in tissues of starry flounder after exposing to the WSF of Cook Inlet crude oil for 3 weeks; post-spawning period. Experiment 3. Cyclohexanes not detectable (< 0.010 μg/g) in control flounder.

Sample	Tissue	Stage	Methyl cyclo-hexane	Cis 1, 3 Dimethyl cyclo-hexane	1, 2 Dimethyl cyclo-hexane	Uniden-tified #1	Uniden-tified #2	C_3 cyclo-hexane	Uniden-tified #3	Total cyclo-hexanes	Total* accumu-lation
			Concentration (ppm)-μg/g (wet weight) Cyclohexanes - (CH)								
1 Female	Ovary	Immature	ND	ND	ND	ND	ND	ND	ND	ND	None
	Liver		27.342	8.882	3.857	ND	1.324	ND	ND	41.405	6900X
2 Male	Testis	Ripe	0.284	ND	ND	ND	ND	ND	ND	0.284	47X
	Liver		38.471	8.455	3.803	0.463	1.310	ND	ND	52.502	8750X
4 Female	Ovary	Immature	0.134	ND	ND	ND	ND	ND	ND	0.134	22X
	Liver		21.615	5.729	2.578	ND	ND	ND	ND	29.922	4987X
9 Male + 10 Male	Testis	Ripe	0.312	ND	ND	ND	ND	ND	ND	0.312	52X
9 Male	Liver		35.867	7.506	3.541	0.029	0.930	ND	ND	47.873	7979X
10 Male	Liver		33.836	6.792	3.011	0.313	ND	ND	ND	43.952	7325X
11 Male + 3 Male	Testis	Ripe	0.384	ND	ND	ND	ND	ND	ND	0.384	64X
11 Male	Liver		31.744	6.842	3.143	0.561	ND	ND	ND	42.290	7048X
12 Female	Ovary	Immature	ND	ND	ND	ND	ND	ND	ND	ND	None
	Liver		31.984	6.863	3.057	0.368				42.272	7045X
Mean Seawater Concentration (mg/L)			ND - 0.006	ND	ND	ND	ND	ND	ND	Max. = 0.006	

ND = Not detectable but may be present. Immature = Ovaries in resting stage.

*Total Accumulation = Tissue Concentration (μg/g)/Maximum water concentration (mg/L).

ESTIMATION OF EFFECTS FROM OIL ON INTERTIDAL POPULATIONS: EXPERIMENTAL PERTURBATIONS VERSUS NATURAL VARIATION

by

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ABSTRACT

Two experimental approaches to the investigation of effects of oil on intertidal population processes were evaluated in terms of effort required to quantitatively estimate effects of specific magnitudes. One approach used trays of oil-contaminated sediment placed in the low intertidal zone and subsequently treated in laboratory tanks. Three polychaete and two bivalve species were evaluated. We concluded that quantitative studies would be feasible using the sediment tray approach but that the cost for high precision would be high. Quantitative studies with the bivalves using the sediment tray approach would be less expensive for given precision than would studies of polychaetes.

INTRODUCTION

Intertidal benthic populations usually receive emphasis in the assessment of oil spill effects because of their vulnerability to surface oil during tidal shifts and high intensity use of intertidal areas for industry and recreation. The potential for lethal and sublethal effects from petroleum on adult and juvenile individuals is amenable to laboratory study, and a considerable literature exists describing such effects. For recent reviews, see Malins (1977) and Anderson (1978). Typically, in laboratory experiments, a logarithmic series

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of concentrations of petroleum hydrocarbons (PHC's) is established, and organisms are exposed to the several concentrations. When statistically significant effects are observed these are ranked as to sensitivity to the total or component PHC's. The ranking is usually in terms of LC50, or a derived index, which quantitates the effect on 50 percent of the test population. Computation of such indices requires that treatment effects be severe enough to be observed in over 50 percent of the test population, and the concentrations are usually unrealistically high both in magnitude and duration.

In attempting to assess the effects of real-world oil spills, the interest is not so much on the individual potential effects as on population processes. These processes may conceivably be altered by oil spillage; conversely, the recovery potential of the populations from impact by oil is an important element in assessment of observed effects. Population recovery processes are not so amenable to laboratory study because the control of perhaps the major limiting variable (environmentally available seed) qualitatively alters the process under study. Recently, two attempts have been made to study the problem of intertidal population processes at our laboratory (Vanderhorst et al. 1977; Vanderhorst and Wilkinson 1977; Anderson et al. 1977). The first of these involved the use of colonized substrates brought into the laboratory and placed in control and experimental tanks continuously treated with No. 2 fuel. The incoming sea water provided a continuous seeding, i.e., opportunity for recruitment. The second attempt involved sediments taken from the intertidal zone, preparation by grading, and either layering or mixing with Prudhoe Bay crude oil. The prepared sediments were then placed in trays, including control trays which received no oiling, and the trays were placed into the intertidal zone for recruitment observations. In both the reported studies, the principal objectives were to investigate the chemical characteristics of the systems and individual effects; population process effects were secondary and largely unfulfilled objectives. An expected high variability in recruitment patterns precluded detection of significant treatment effects in most cases. Nevertheless, the data generated provide a basis for the design of similar experiments with the objective of investigating population processes.

Since a failure to detect significant effects in the foregoing studies may lead to either of two conclusions, i.e., there were no effects; or, the methods used were not sensitive enough to detect effects, it is the goal of the present study to estimate the sensitivity of the methods used for measuring population effects and to estimate required effort in terms of numbers of samples to measure specific magnitudes of change in density. Although changes in density alone will not allow quantitation of population processes, it is a prerequisite for which these estimates are pertinent.

MATERIALS AND METHODS

Sediment-Tray Experiments

We will refer to the experiments of Anderson et al. (1977) as sediment-tray experiments. Details of preparation, installation, and chemical analyses were described in the publication. In general, sediments were collected from the beach in an intertidal zone of Sequim Bay, which was subsequently used for installation of the prepared sediment trays. The sediments were seived to increase homogeneity and were treated in one of three ways. Control trays were prepared by placing seived sediments in fiberglass or polyvinylchloride open-top boxes (32 x 10 x 17 cm). Control trays were placed at the approximate mean lower low water level adjacent to each experimental installation. In the first two experimental installations, seived sediments received a surface application of 4% (V/V) Prudhoe Bay crude oil in the laboratory. Excess oil was flushed from the surface, and the trays were placed into the intertidal zone for observation of recruitment. The third experimental installation involved thorough mixing of oil (0.1%) and sediment, using the method of Anderson et al. (1977). Observations on recruitment for all installations involved subsampling trays with cylindrical cores (3.8 cm inside diameter). Usually, three cores per sediment tray per sampling period were taken. Sampling extended for a period of more than a year.

Although numerous incidental species were identified from core samples, there was reasonably consistent occurrence only for the two bivalves (a juvenile and mature cohort), *Psephidia lordi* and *Mysella tumida*; and the three polychaetes, *Ophiodromus pugettensis*, *Armandia bioculata*, and *Platynereis bicanaliculata*. The analyses applied here are limited to these species and cohorts.

Colonized-Brick Experiments

The studies of Vanderhorst et al. (1977) and Vanderhorst and Wilkinson (1977) are referred to as the colonized-brick experiments. Details of preparation, treatment, and chemical description can be found in the publications, and further chemical description is in Bean and Blaylock (1977). In general, these studies involved colonizing concrete construction bricks (19 x 9 x 6 cm) in the intertidal zone, placing the colonized bricks in continuously flowing seawater tanks, some of which received a continuous flow of No. 2 fuel (100 ppb and 600 ppb, physically dispersed) and observing numbers and kinds of organisms on bricks over a six-month period. Sampling was by removal of one brick from each tank at the end of each month of exposure. All species were identified and enumerated. Among those species, numbers of the five species for which we have data in the sediment-tray experiments, are here analyzed.

Statistical Procedures

Snedecor and Cochran (1967) recommend a square-root transformation when count data are analyzed. Since the data here considered are all counts, primary data were transformed:

$$X = \sqrt{X + 1} \quad (1)$$

All analyses here reported are on the transformed variable, and percentage differences indicated are for the transform.

Disregarding omissions, the sampling schemes for the two experimental approaches are similar. The estimation of sampling requirements or measurement of effects is a two-stage process in each instance. Treatments were applied to sediment trays in one case and to tanks in the other. These are the experimental units. Treatment effects and/or estimation of numbers of units required to detect changes using the approaches are expressed in terms of these units. The second stage of the problem relates to subsampling the experimental units to estimate change within a particular unit.

For the sediment tray experiment, experimental units are trays. Instances when more than one tray received the same treatment and was sampled on the same date are limited to treated units. To estimate between tray variance, trays were paired for treatment and for date of sampling. A variance for each pair was determined. An average of variances so obtained represents our estimate of between-units variance. For an estimate of the within unit variance, a variance was computed for the cores within each unit (n = 3; in a few instances, n = 4). An average of the variances so obtained over all units represents our estimate of within units variance. There were 12 units for each average so obtained.

For the colonized brick experiment, one and only one brick was removed from each unit (tank) at each sampling period. No estimate for within unit variance is therefore possible. Between unit variance is estimated in a manner similar to the above. Triplicate controls were sampled at each interval. A variance was computed for each interval group, and an average of these variances is our estimate of between unit variance.

The data were evaluated in a framework suitable for testing hypotheses about differences due to treatment. In our experiments, like many field studies of oil pollution, apparent differences due to treatment were small and obscured by a large amount of variability. Thus, our interest centered as much on the failure to detect a true difference, should it have occurred, as on the significance of

differences observed. This interest involves an estimation of "power of the test" or, conversely, the probability for commission of a Type II statistical error. We made these estimates from tables supplementary to Kastenbaum et al. (1970) which provide tabular values of the standardized range relative to significance levels (alpha), probability for a Type II error (beta), and sample size.

RESULTS AND DISCUSSION

Sediment-Tray Experiments

This approach is most useful for our purpose since it provides data to estimate the variances for both stages of sampling. We will first examine the relative magnitude of differences between control and treatment to which the method might be suited. We use as an example on Figure 1 data for the combined cohorts of Psephidia lordi. The figure

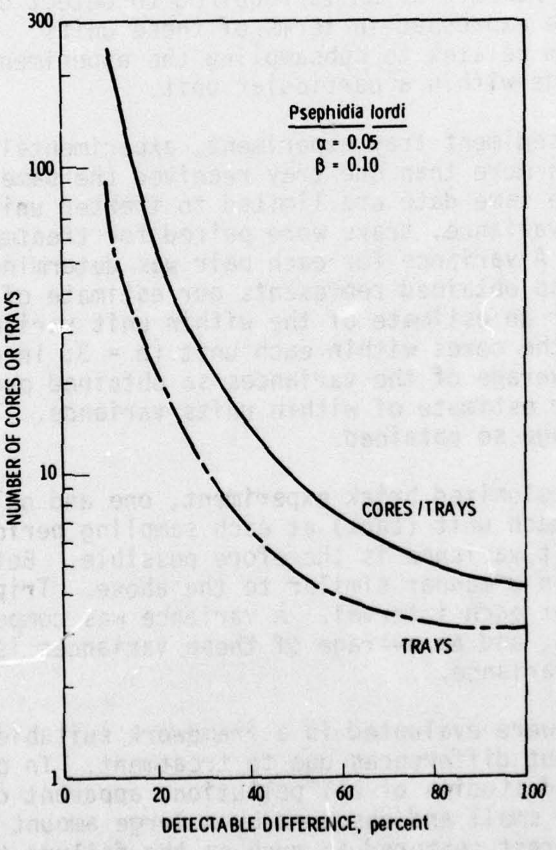

FIGURE 1. Percent detectable differences in density of *Psephidia lordi* as a function of sample size.

is a plot of the percentage difference detectable between two means, using the numbers of trays indicated to measure significant (alpha = 0.05) treatment differences and the numbers of cores indicated to measure significant (alpha = 0.05) differences within trays with a ten percent risk of not detecting a true difference of the magnitude indicated. The maximum observed difference in mean numbers of P. lordi in the experiment, which might be related to treatment, was 51 percent. The sensitivity of the experiment as conducted for this species obviously fell short on both treatment differences and within tray differences, since we had two experimental units which were contaminated and one experimental unit as control, and removed three cores from each unit.

As is apparent from Figure 1, when estimates of variance are established and risks are set, the numbers of samples required to detect smaller real differences (at the lower end of the scale) increase logarithmically. For studies like the sediment tray experiment in which examination of single cores is time consuming, and preparation and detailed chemical characterization of the units is extremely expensive, it behooves the investigator to establish moderate expectations of method sensitivity. For purposes of comparison with other examples in this experiment, we will use a detection sensitivity of 50 percent. Fixing this variable will allow us to manipulate significance and power, and compare sensitivities among species and cohorts. We have chosen the 50 percent level because it is representative of some of the observed changes, because it is intuitively comparable to toxicity measures used in laboratory studies, e.g., LC50, TL_m, and because a real change of 50 percent in natural populations would be construed as important by many biologists.

The amount of effort required to detect a 50 percent difference in control and treatment means (total 10 trays and 100 cores per sampling interval) would be feasible for a species in which there was a great deal of interest but would not be practical for species of passing interest. To further compound the issue, our example species is a very common one in the Puget Sound region; this raises the question of whether a true 50 percent reduction locally would have any biological meaning.

For common species with little or no commercial value it behooves the investigator to arrive at some way to reduce the effort if he is to examine population effects in quantitative terms. One way to reduce effort is to increase the risk of being wrong about statements of effect. On Figure 2, we have plotted the data for the combined cohorts of P. lordi at a detection sensitivity of 50 percent with power (inverse of Type II error probability) as a function of sample size when the significance level of the test is 0.05 and 0.10. The steep slopes to the left of the figure indicate that power above 90 percent is increasingly expensive in terms of numbers of samples, while increases from 60 to 80 percent are not so expensive. At a power of 90 percent, reduction of the significance level to ten percent from the conventional five percent results in a reduction in need for

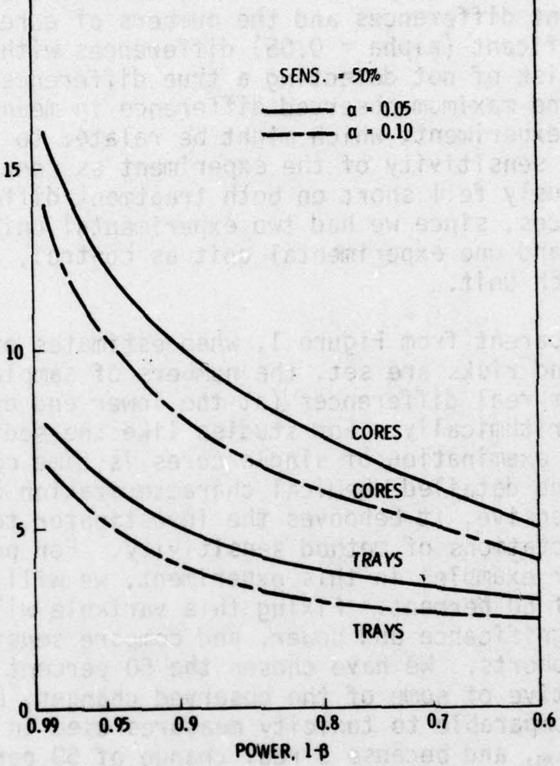

FIGURE 2. Probability of detecting a 50 percent difference in density of Psephidia lordi related to sample size.

samples from ten to eight cores per tray, and from five to four trays to detect the treatment effect. In the complex experimental designs which will be needed to properly investigate recruitment or other population processes, this is a very substantial saving.

Choice of risk factors will depend on several things. The point of view may influence the balance of error probabilities selected. A higher risk for not detecting a true effect (lower power) may be acceptable to a potential pollutor. Regulators may be willing to assign a higher risk for wrongly identifying an effect as significant. From a more objective standpoint, the finality of the decision may be important in establishing risk. For example, for an operating plant to be closed because of a study, the significance level should be one of high certainty. In the case of oil spillage, which is a one-time event, detection of true effects seems at least as important, and for research with the primary objective of detecting effects, a balance of error probabilities seems most appropriate. We have, therefore, used balanced risks of ten percent for both errors for the remaining comparisons presented here.

On Figure 3 are plotted numbers of cores per tray required to detect a true 50 percent difference in tray mean with ten percent risk on each error. Sample sizes for bivalves are remarkably consistent (7 or 8) regardless of species or cohort. The range in projected

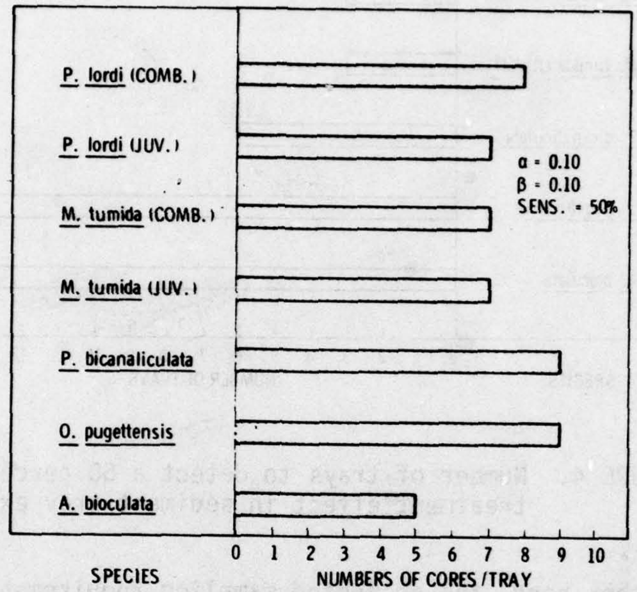

FIGURE 3. Number of cores required to detect a 50 percent difference in tray density.

sample size for polychaetes is slightly larger (5-9 cores) but could very well be attributable to the crudeness of our estimate of variance for the different species. Seven cores represent about 15 percent of the total area of a tray. Thus, in design of a future experiment, one would need to weigh the risks (10%) and magnitude of tray change detectable (50%) against a factor of about seven for the increased effort of examining the total tray content to eliminate this source of variance. For the very small animals being studied in the reported experiments, this might represent as much as four additional man-weeks of effort per tray estimate and, in our view, would be a decision of dubious merit.

Figure 4 provides data for estimation of sampling requirements to measure treatment differences, i.e., numbers of trays per treatment mean. Estimates for the bivalves range from three to six trays per treatment mean. Slightly higher estimates can be observed for *P. lordi*, particularly the juvenile cohort. We judge these estimates to be reflective of the imprecision of our estimate of the true variance.

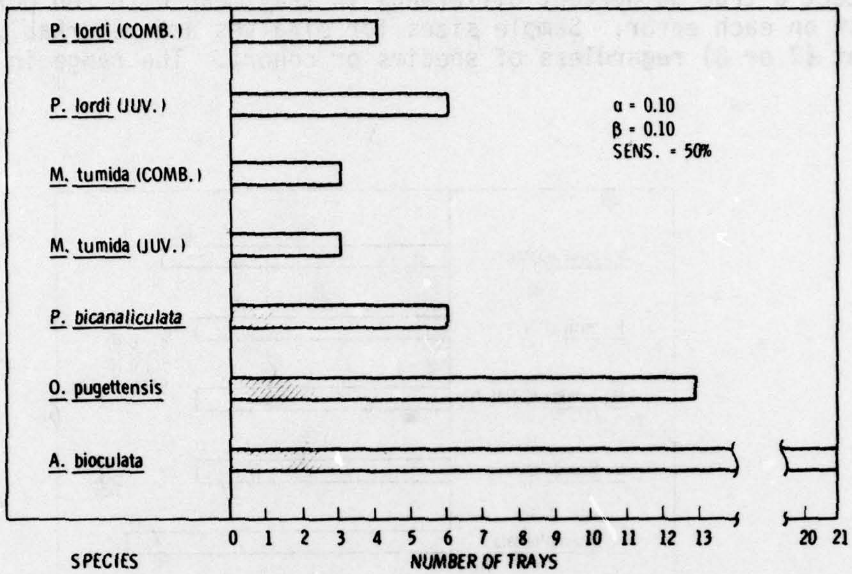

FIGURE 4. Number of trays to detect a 50 percent treatment effect in sediment tray experiment.

On the other hand, the projected sampling requirements for polychaete species range from two to seven times the numbers of trays needed for detecting equivalent differences in bivalves. We believe this is a reflection of real differences in the settlement and movement patterns for the polychaetes as compared to the bivalves, and that a greater number and/or larger trays will be needed in an experiment with the goal of detecting differences in density of 50 percent or less due to treatment.

Colonized Brick Experiment

The first results presented here relate to the general sensitivity of the approach. On Figure 5 are the numbers of tanks required to detect specified differences due to treatment for the best and worst cases with ten percent risk on each error. For the bivalve, Psephidia lordi, the required number of tanks is substantial, and even for differences as large as 200 percent, triplicate tanks are required. There is justification for considering these larger percentage differences when using the continuous-flow system as compared to the sediment-tray experiment, since the severity of treatment may be adjusted to produce larger effects in much the same way conventional oil bioassays have done it, i.e., a logarithmic series of concentrations of contaminant may be used for exposure.

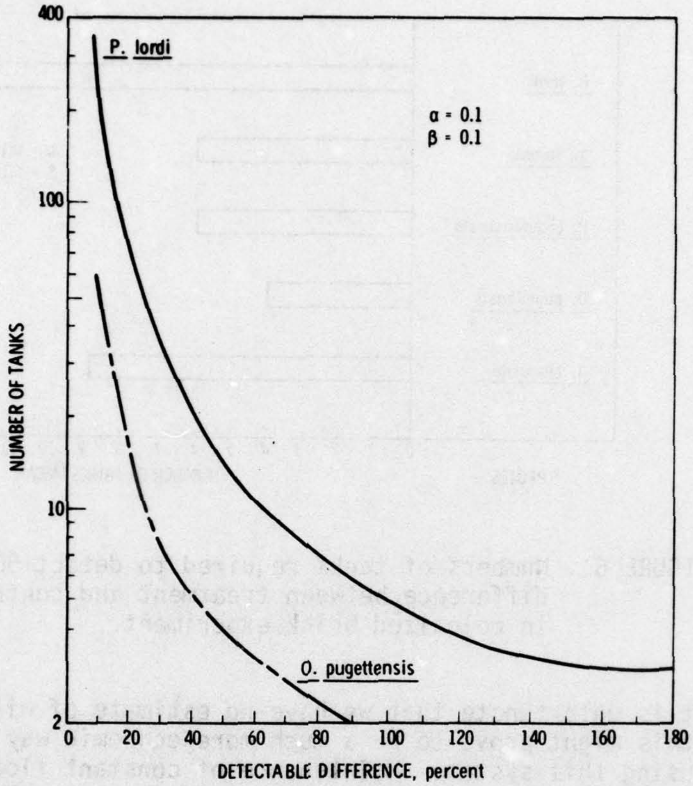

FIGURE 5. Number of tanks to detect percent differences in treatment and control means for Psephidia lordi and Ophiodromus pugettensis.

Detection of differences for the polychaete, O. pugettensis, will require much less effort in the system, i.e., a 90 percent difference in density could be detected with the two replicate treatment tanks used in the primary experiment (Vanderhorst et al. 1977). This apparent anomaly, or reversal of sensitivity for the polychaete and bivalve in this system versus the sediment-tray system, most likely relates to the suitability of the differing habitats for the species in question.

A comparison of the numbers of tanks needed to detect 50 percent treatment differences for the five species studied is on Figure 6. The range is from four tanks for O. pugettensis to 15 tanks for P. lordi. There is not a consistent pattern in sensitivity of the methods for either of the major taxonomic groups. It is apparent that the experiment originally conducted (two tanks at each treatment concentration) would not have been expected to produce quantitatively significant results.

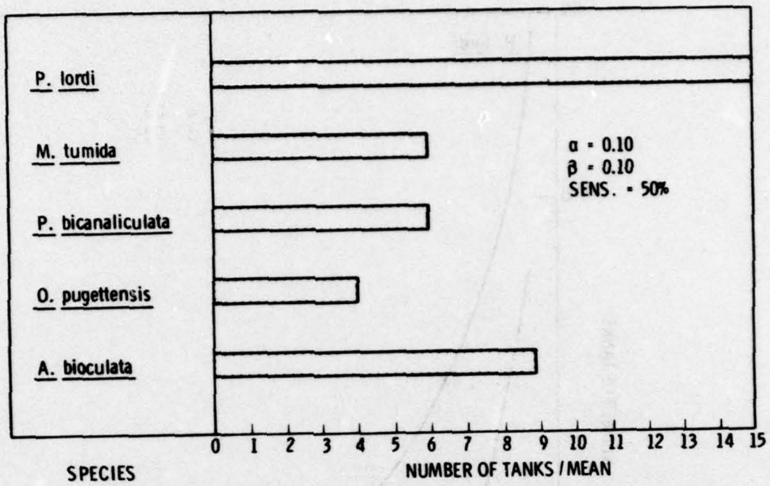

FIGURE 6. Numbers of tanks required to detect 50 percent difference between treatment and control means in colonized brick experiment.

It is unfortunate that we have no estimate of within tank variance since this might prove to be a much more economic way to design experiments using this system. Maintenance of constant flows and quantities of contaminant sets a low practical limit to the numbers of tanks which can be used.

CONCLUSIONS

We have presented data from two experimental systems possibly suitable for the investigation of the effects of oil on intertidal benthic population processes. The experiments from which we drew data were designed for purposes other than the approach to the problem presented here. We offer no excuse for our inability to conduct a balanced analysis of variance to arrive at appropriate estimates of variance associated with season or, in the case of the sediment tray experiment, the severity of treatment. The utility of this analysis lies in three general areas: (1) a definition of the relative effort required to investigate population processes in field experimental or recruitment open systems; (2) a demonstrated application of statistical power concepts to petroleum effects studies; and (3) data useful for setting of goals in attempting field assessments of the effects of oil spillage on marine intertidal biota.

The relative magnitude of effort for measuring effects on population processes as exemplified by the present approaches is high. We have addressed the single problem of density estimation at a given

instant in time. Quite naturally, interest in effects of oil on benthic recruitment will involve multiple estimates through time. It may well be that effective experimental design (allotment of treatments and blocking) will reduce sample size per unit. It is very unlikely, however, that a complex design will result in reduction of effort below that used in the present studies overall. There is a strong need to evaluate the effects of petroleum on population processes since populations, not individuals, are the units used by man and enhance or degrade the quality of the marine environment. The data from this study demonstrates that estimates of density using the methods used are feasible. Choice of the sediment tray approach over the colonized brick approach is preferred based on these analyses of sensitivity.

The use of statistical power concepts in the design of experiments to study effects of oil on intertidal populations has not been used with the exception of a recent report (Moore et al. 1978) which gave primary emphasis to experimental design. That study, although elegant, was seriously hampered by a lack of data on the possibly selective effects of oil on the populations in question. In conventional bioassay work, power concepts have not been needed because of the relative ease with which screening bioassays can be conducted to arrive at suitable treatment effects. Clearly, the costs for even screening bioassay of population processes precludes the use of such a nonsystematic approach. The data in this study, however crude, provide an application of probability theory to a real oil effects data set. It is also suggested that because of the steepness of the curves of required samples against detection sensitivity at error risks from 0 to 10 percent, that risks for both errors of at least ten percent be adopted. There is a long history of the acceptance of the five percent significance level as being the "magic" number where effects become real. In contrast, the probability of the corollary Type II error is almost never computed. For the objective of detecting effects, it is the latter error which is critical.

Because power of the statistical test is critical to detection of effects, this study bears relevance to the design and interpretation of field studies of oil spillage. With a few notable exceptions (e.g., Russel 1972; Lichatowich 1976; Vanderhorst and Wilkinson 1978), field studies of pollutant effects (including oil spillage) do not state the sensitivity of the methods. This means that one of two general conclusions may be reached, i.e., "there were significant effects," or, "significant effects were not detected." In the former case, there is no indication as to how severe the effect had to be to be significant; in the latter case, there are two possible interpretations: (1) there were not any effects; or (2) the methods were not sensitive enough to detect the effects. In absence of a statement of method sensitivity, objective basis for improvement of the next survey or experiment is not possible.

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INTRODUCTION

An important aspect of oil spill assessment should involve some evaluation of chemical contamination in affected organisms, particularly so for edible species. Such contamination is best evaluated through the study of hydrocarbons (HCs), although tainting by non-hydrocarbon constituents could be significant in certain instances.[2,5]

Most organisms possess a specific array of HCs, resulting from everyday metabolic processes, which must be recognized when considering the chemical impact of spilled oil. Our understanding of such hydrocarbon arrays is poor, especially within marine forms.[8,9] As a prelude to increased extraction, transport, and potential spillage of petroleum in southern California waters, we have begun to examine high molecular weight HCs (C_{14}-C_{34}) in bottom-dwelling invertebrates, in an attempt to gain some understanding of their natural distribution within several animal groups.

METHODS

Organisms were collected throughout 1975-76 with bottom trawls at depths from 30 to 1900 meters, and stored at -20°C until analysis. Hydrocarbons were analyzed according to procedures detailed in Rossi _et al._,[7] which involved overnight saponification in methanolic-KOH, extraction into n-hexane and isolation via liquid chromatography. Gas chromatography entailed use of a Hewlett-Packard Model 5830A instrument, equipped with a linear temperature programmer and an electronic integrator. S.C.O.T. stainless steel OV-101 capillary columns were used. Conditions for analyses were: oven temperature programmed from 120°C to 280°C at 4°C per minute, and held isothermal at 280°C for 35 minutes, nitrogen carrier gas flow was 4.1 ml/min, injector temperature 290°C and detector temperature 300°C. Combined gas chromatographic-mass

Table 1

Gravimetric data for benthic invertebrate samples. Hydrocarbons determined by gas chromatography, expressed in μg/g dry wt. Mean values for *n* number samples.

Common name	Fresh weight (g)	Dry weight (g)	D.W./F.W. (%)	*n*	Non-saponifiable lipids (mg)	N.S.L./D.W. (%)	Total hydrocarbons (μg/g)
Anemone (*Paractus* sp.)	33.52	5.36	15.9	3	78.0	1.45	19-71
Spider crab (*Paralithodes* sp.)	56.36	13.83	24.5	5	113.5	0.82	44-512
Green snail (*Bathybembrix* sp.)	50.96	18.61	36.5	4	36.8	0.20	21-554
Heart urchin (*Brissopsis* sp.)	60.65	28.8	47.5	6	66.7	0.23	29-4836
Pink urchin (*Allocentrotus* sp.)	56.26	16.15	28.7	5	47.6	0.29	37-394
White urchin (*Lytechinus* sp.)	59.86	18.28	30.5	3	41.4	0.23	64-158
Mud starfish (*Luidia* sp.)	75.00	20.58	27.4	7	143.7	0.70	89-2660
Knobby starfish (*Myxoderma* sp.)	37.87	12.41	32.8	7	64.3	0.52	34-480
Sea cucumber (*Scotoplanes* sp.)	35.33	7.53	21.3	4	8.2	0.11	38-175
Colonial sea squirt (*Dromallia* sp.)	25.64	1.96	7.6	6	7.2	0.37	4-236

spectrometric analyses were conducted on a Hitachi M-52 GC/MS interfaced with a LOGOS Spectrotek DS-200 data system, by A. L. Burlingame. Contamination-free procedures were employed throughout, and verified by frequent testing of blanks.

RESULTS

Twenty-six invertebrate species, taken from 60 different sites throughout the southern California continental shelf region, were analyzed. Data from ten representative species are treated in Table 1. Invertebrates demonstrated a wide range of total hydrocarbon concentrations (hexane + benzene eluates). Low values (4-89 μg/g) were observed in animals collected from outer (offshore) provinces, such as Tanner-Cortez Banks and southern shores of San Miguel/Santa Rosa islands (Figure 1). Maximum values (71-4836 μg/g) were generally noted in nearshore (coastal) samples, and greatest in those species which nestle within bottom sediments (heart urchins and mud starfish). Lipid-rich forms (anemones and crabs) were characterized by moderate HC levels.

Comparison of total and synthetic HCs in five species, sampled offshore as well as near the coast, demonstrates the effect of nearshore hydrocarbon inputs on invertebrate HCs (Table 2). For all species, total

TABLE 2

Total and synthetic hydrocarbons in selected invertebrate species, sampled from outer continental shelf or nearshore (coastal) sites. Station numbers in parentheses. Values in μg/g dry weight.

Species	Station	Total hydrocarbons	Total synthetic hydrocarbons
Spider crab	Coastal(214)	353	20.7
	OCS(673)	44	4.3
Heart urchin	Coastal(377)	4836	35.6
	OCS(723)	29	0.5
Pink urchin	Coastal(406)	394	7.0
	OCS(661)	64	3.1
Mud star	Coastal(374)	990	18.8
	OCS(65)	89	3.5
Sea squirt	Coastal(330)	236	5.6
	OCS(599)	4	0.4

and synthetic HCs in nearshore samples greatly exceeded those from the outer shelf. Values for total synthetic hydrocarbons were derived by summing amounts of all DDT derivatives, plasticizers, and polychlorinated biphenyls. Invertebrates from nearshore provinces characteristically displayed complex profiles with large bimodal unresolved complex mixture (U.C.M.) signals (apexes of 1900 and 2400, OV-101), superimposed by elevated numbers of resolvable compounds (Figure 2). Animals from outer provinces were distinguished by very low U.C.M. signals and fewer resolvable components, excepting samples contaminated by petrogenic compounds (Figure 2).

Some frequently used criteria for distinguishing biogenic and petrogenic HC profiles were applicable to most samples, for both hexane and benzene eluates.[2,3,11] These criteria are applied to data from analyses of a starfish, sampled from three distinctly different provinces (Tables 3 and 4). Total, branched, and *U.C.M. hydrocarbons* were lowest in starfish from the outer Banks region, and greatly elevated in Coal Oil Point and Pt. Fermin samples. Pristane and odd-numbered carbon chain length n-alkanes were important constituents in outer Bank starfish, their relative contributions decreased in nearshore animals. Phytane was present only in coastal starfish. Within benzene

TABLE 3

Analytical ratios for F_1 (hexane eluate) fractions of the knobby starfish, *Myxoderma platycanthus*, sampled from three representative stations (in parentheses). Values in μg/g dry weight. U.C.M. = unresolved complex mixture (signal) hydrocarbons. nC = normal alkane.

	Tanner Bank (572)	Coal Oil Point (193)	Pt. Fermin (373)
Total F_1 hydrocarbons	15.1	153.1	360.6
U.C.M.	9.1	130.4	317.5
Resolved hydrocarbons / U.C.M.	0.66	0.17	0.10
Pristane	0.5	0.8	0.4
Pristane/nC-17	20	1	0.8
Phytane/nC-18	Not present	1	0.75
Odd nC/Even nC	4	1.8	2.3
Branched Alkanes / Normal Alkanes	0.3	3.5	6.2

eluates (Table 4), synthetic hydrocarbons were important components in starfish sampled from Pt. Fermin, proximal to a major submarine sewer outfall. Unique to these nearshore samples were the plasticizers dioctyl adipate (DOA), dioctyl phthalate (DOP), and butylphthalyl-butyl-glyoxylate (BPBG). A biogenic terpene, squalene, was present at similar levels in all three samples.

TABLE 4

Analytical ratios for F_2 (benzene eluate) fractions of the knobby starfish, *Myxotherma platyacanthus*, sampled from three representative stations (in parentheses). Values in μg/g dry weight. U.C.M. = unresolved complex mixture (signal) hydrocarbons.

	Tanner Bank (572)	Coal Oil Point (193)	Pt. Fermin (373)
Total F_2 hydrocarbons	18.9	60.2	119.4
U.C.M.	3.9	25.4	91.3
Resolved / U.C.M.	3.8	1.4	0.3
Total PCBs	0.1	0.7	4.4
P,p-DDE	0.2	13.2	2.9
P,p-DDT	N.D.	0.3	N.D.
DOA	N.D.	N.D.	4.4
DOP	N.D.	N.D.	0.6
BPBG	N.D.	N.D.	0.2
Squalene	0.3	0.2	0.3

The impact of submarine sewer discharges on faunal HCs is further demonstrated in Table 5 where results from two closely related urchins are given as a function of distance from the closest submarine outfall (Hyperion, White's Pt., or Orange Co.). Total, branched, U.C.M., and synthetic hydrocarbons declined with distance from an outfall. The most dramatic change was observed among branched alkanes (generally absent from unpolluted marine invertebrates), which decreased in relation to normal alkanes by nearly two orders of magnitude.

Concentrations of three compounds of presumed recent origin are presented for comparison.[1,10] A biogenic origin for pristane, heneicosahex(-pent)aene (HEH + HEP), and squalene is supported by the observation that their levels do not appear related to distance from an outfall, or other suspected sources.

TABLE 5

Hydrocarbon parameters for sea urchins as related to distance of collection site from nearest major sewer outfall. Values in μg/g dry weight, derived from analyses of *Allocentrotus fragilis* and *Brissopis pacifica.*

	Distance from Outfall (km)					
	<5	5-10	25-50	50-100	100-125	>140
Total hydrocarbons	4836	2050	519	229	90	33
Resolved / Unresolved	0.07	0.15	0.22	0.32	0.46	0.82
Branched Alkanes / Normal Alkanes	6.1	5.7	2.0	1.9	1.3	0.05
Total DDT	10.6	3.1	3.0	1.1	0.2	0.2
Total Phthalates	7.6	6.8	3.5	1.6	1.3	0.5
Pristane	7.4	8.2	2.4	9.0	5.9	4.7
HEP + HEH	2.3	5.8	13.4	7.4	6.1	12.4
Squalene	8.8	13.4	12.5	5.0	5.2	13.3

DISCUSSION

Results of these studies indicate a wide range of hydrocarbon profiles exists among benthic invertebrates encountered within the southern California continental shelf benthos. Uncontaminated animals generally contained less than 100 μg/g total HCs, and exhibited characteristics attributed to biogenic constituents, e.g., low U.C.M. values, an absence of branched alkanes and phytane, and a predominance of odd-numbered n-alkane chain lengths. Significant differences in uncontaminated profiles were related to species specific variations. Elevated levels of HCs observed in burrowing species (urchins, some starfish) suggest the inclusion of unaltered sediment into analysis. Unless steps are taken to preclude such contamination, the value of these forms as true "biological-monitors" would appear questionable.

Nevertheless, their use could provide information on the composition of sediments to which organisms are actually exposed.

Anthropogenic inputs (sewer outfalls, river runoff, atmospheric fallout) strongly modified invertebrate hydrocarbon profiles. This effect was most pronounced in samples taken nearest such sources. The composition of sediments throughout the bight likewise reflects this influence.[6] Polychlorinated biphenyls and p,'p'-DDE appear to be ubiquitous components within the lipid pools of southern California benthic invertebrates, whereas the less *refractory* plasticizers (DOA, DOP, BDBG) seem restricted to organisms taken from the inner coastal provinces.

Biochemical data presented here support recent findings by geochemists that a heretofore undocumented large number of submarine oil seeps could exist within the study area.[4,6] Compositional features attributed to petroleum were observed in numerous samples taken not only adjacent to Coal Oil Point (known seeps), but also in organisms from the outer Banks region, as well as the south-east shores of Santa Rosa Island. These results are graphically presented in Figures 4 and 5. Such findings suggest the need for site specific sampling when attempting to establish pre-development criteria, especially within tectonically active (seep-prone) regions such as the southern California borderlands.

ACKNOWLEDGMENTS

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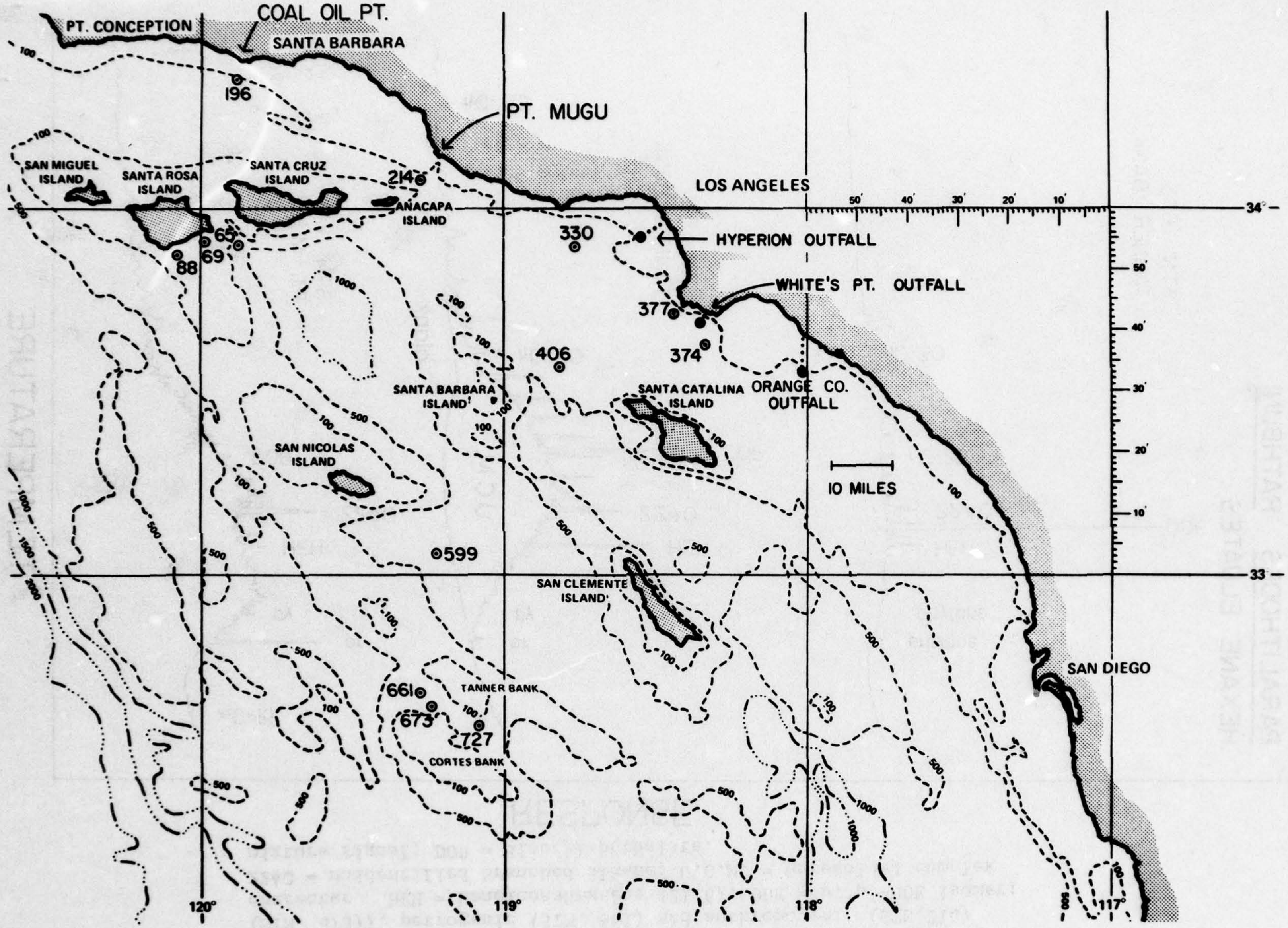

Figure 1. Index map of the southern California bight showing (selected) sample locations with respect to submarine sewer outfalls and bathymetry.

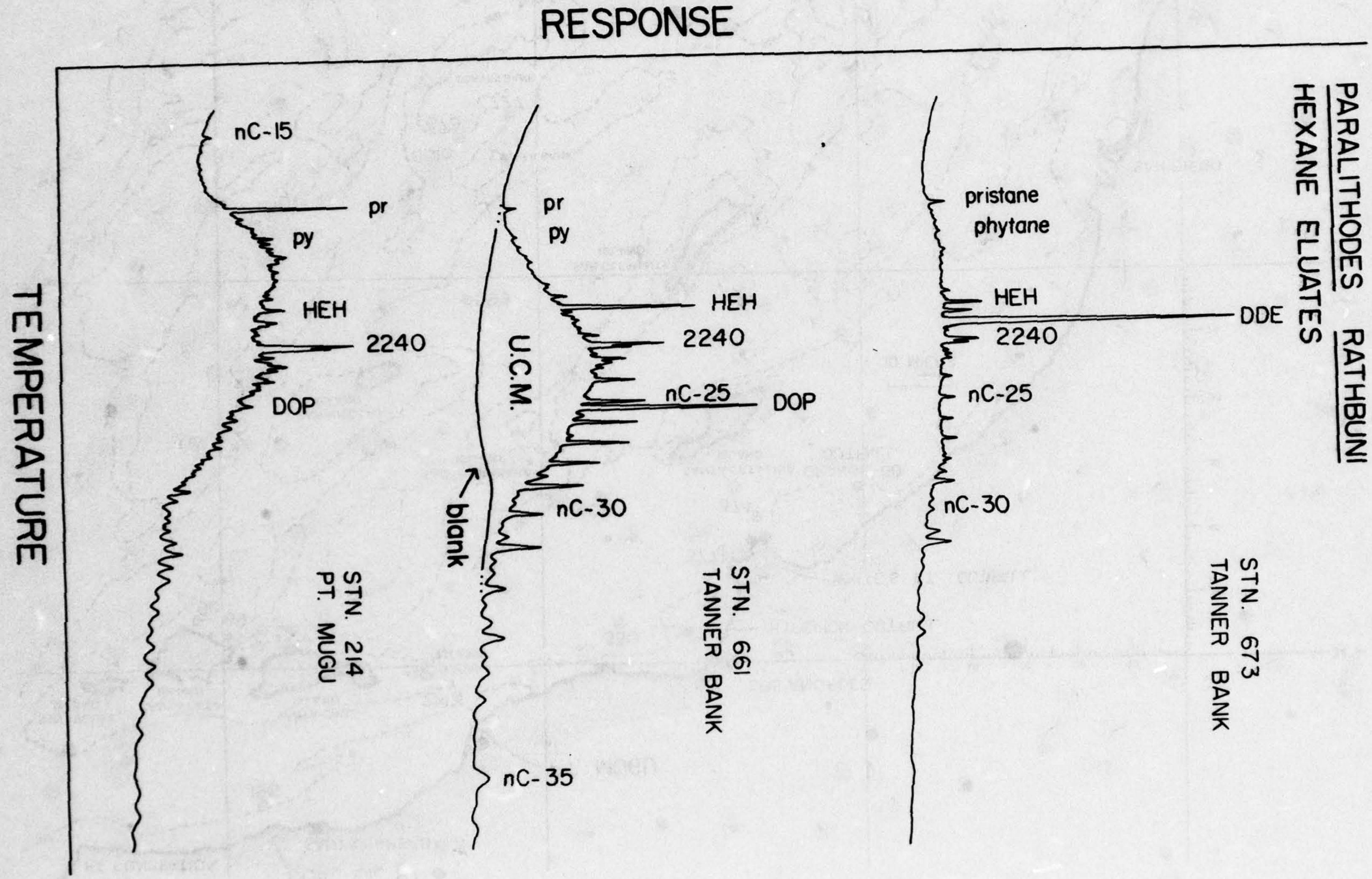

Figure 2. Reconstructed gas chromatograms of hexane eluates from a spider crab species showing hydrocarbon profiles of biogenic (STN. 673)), petrogenic (STN. 661) and anthropogenic (STN.214) character. HEH = heneicosahexaene (21:6); DDE = p,'p'-DDE isomer; 2240 = unidentified branched alkene; U.C.M. = unresolved complex mixture signal; DOP = dioctyl phthalate.

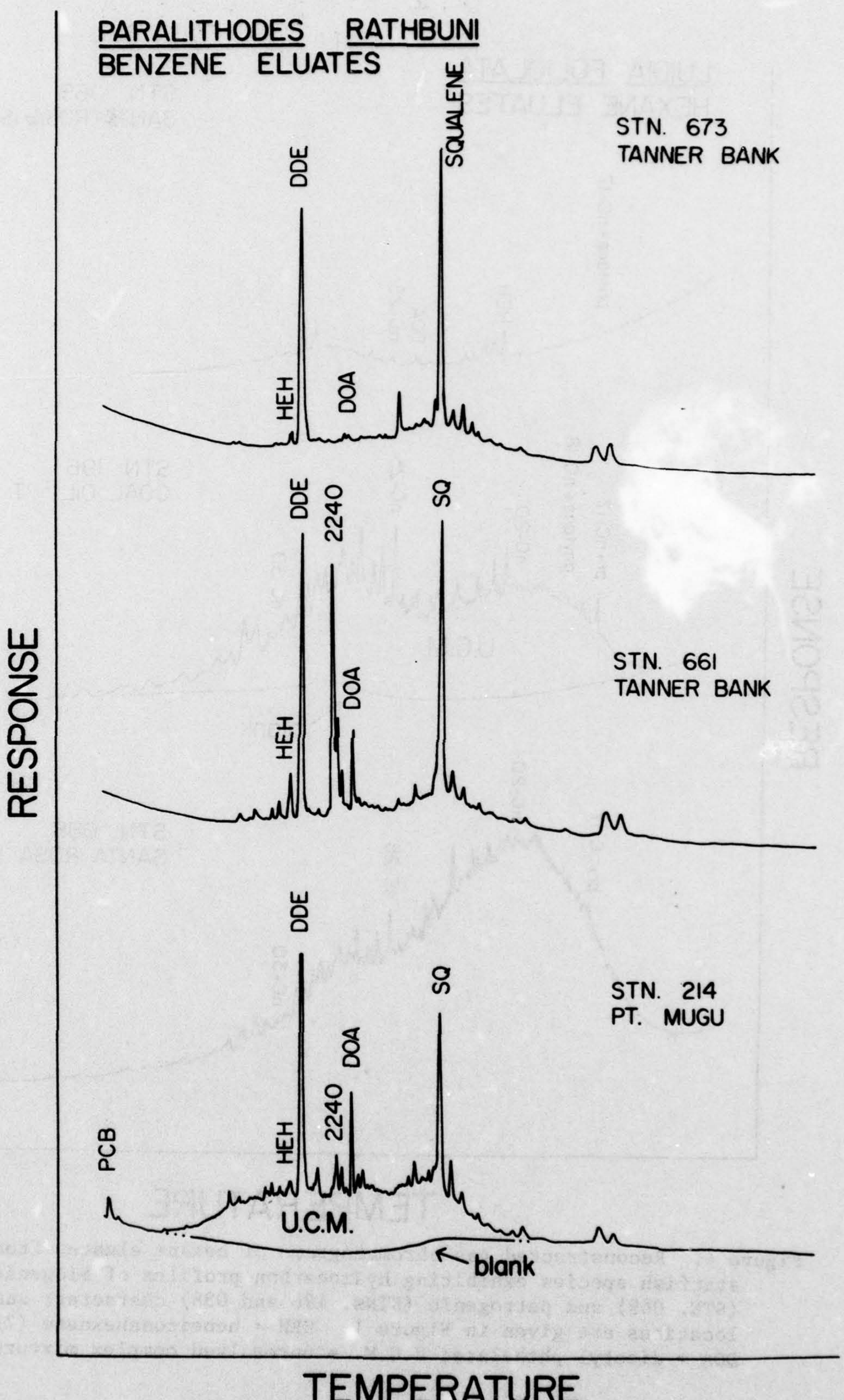

Figure 3. Reconstructed gas chromatograms of benzene eluates corresponding to extracts given in Figure 2. DOA = dioctyl adipate.

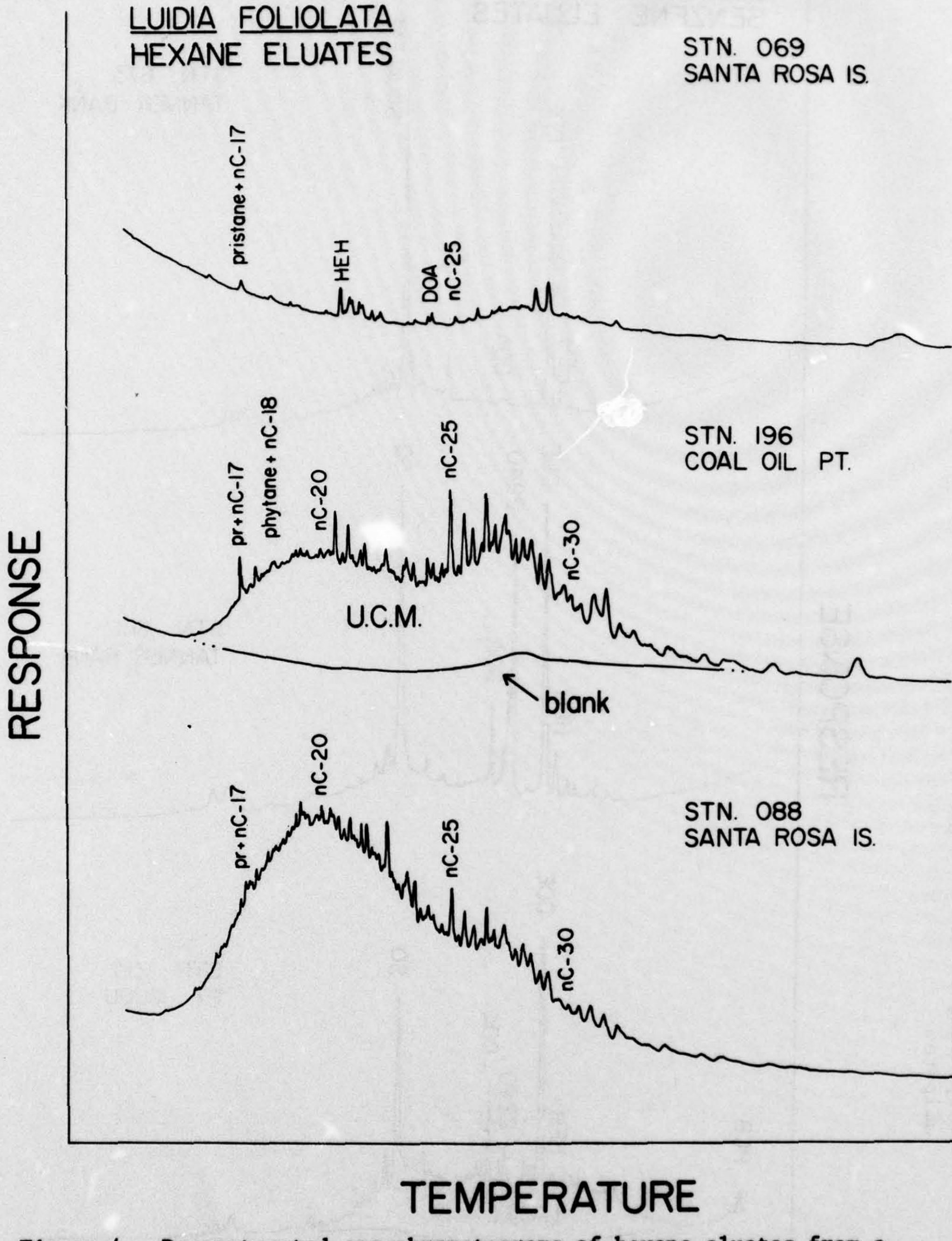

Figure 4. Reconstructed gas chromatograms of hexane eluates from a starfish species exhibiting hydrocarbon profiles of biogenic (STN. 069) and petrogenic (STNs. 196 and 088) character; sample locations are given in Figure 1. HEH = heneicosahexaene (21:6); DOA = dioctyl phthalate; U.C.M. = unresolved complex mixture signal.

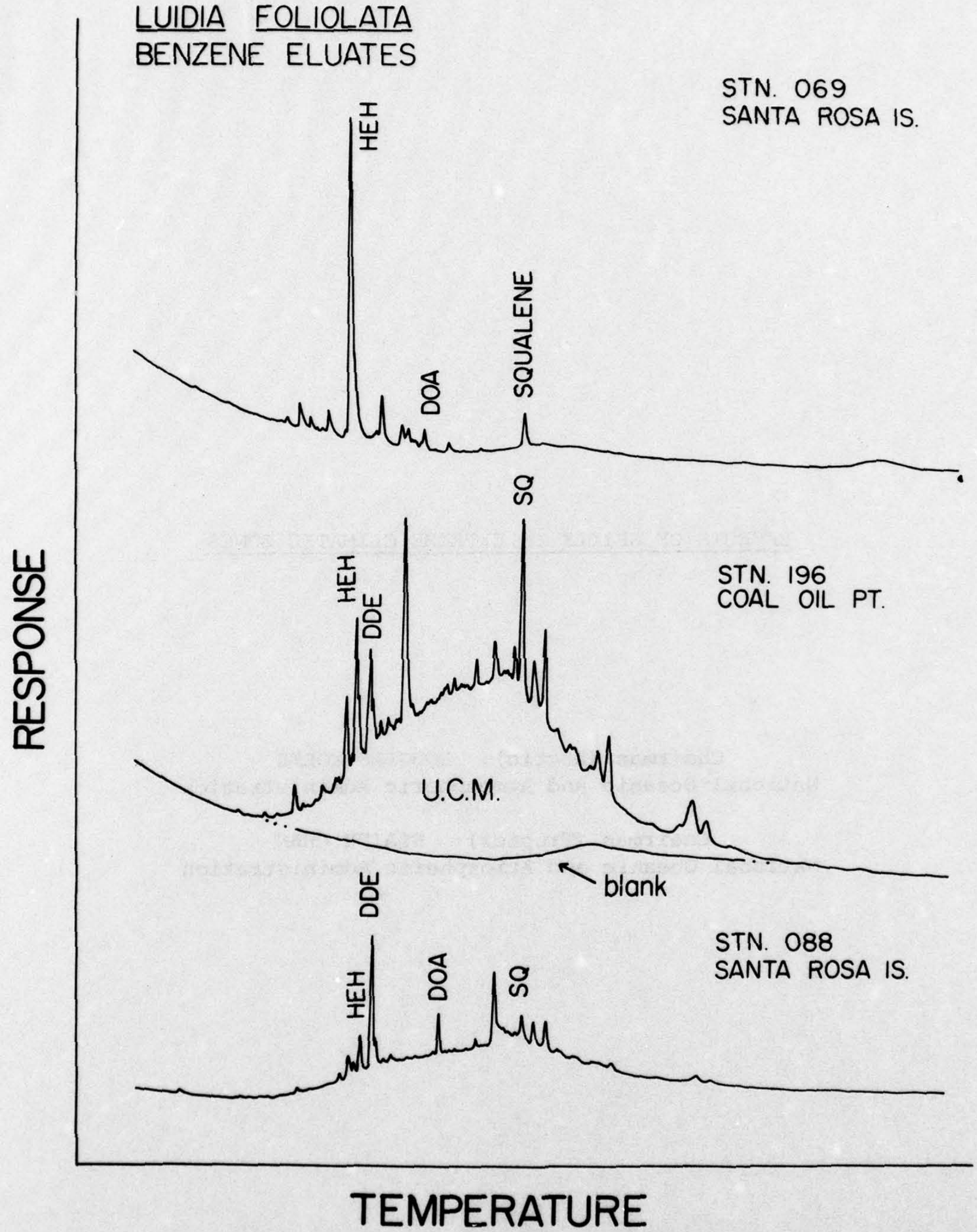

Figure 5. Reconstructed gas chromatograms of benzene eluates corresponding to extracts given in Figure 4. DDE = p,'p'-DDE isomer.

EFFECTS OF SPILLS IN EXTREME CLIMATIC ZONES

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Chairman (Tropics): ELAINE CHAN
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ASSESSMENT OF THE ECOLOGICAL EFFECTS OF AN OIL SPILL IN AN OFFSHORE SUBARCTIC ENVIRONMENT

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ABSTRACT

The waters of the eastern Canadian arctic and subarctic, Baffin Bay, Davis Strait, and Labrador Sea hold the potential for large, as yet undiscovered oil and gas formations. Since 1976 a program of field studies and investigations have been undertaken in the Davis Strait region that is intended to gather data to assist in designing the technology of a drilling system and which will be used to assess the ecological implications of drilling in the area. Utilizing this data, and based on oil spill scenarios developed for various hypothetical oil spill stituations, an assessment was prepared as part of the development of an environmental impact statement (EIS).

INTRODUCTION

As in many other parts of the world, the search for oil and natural gas in Canada is being extended increasingly into offshore waters. In the Canadian arctic, offshore exploratory drilling has taken place from man-made islands, strengthened ice platforms, and drillships. On the east coast, extensive offshore drilling has taken place, with somewhat disappointing results to date. Figure 1 shows the offshore areas of Canada where exploratory drilling has taken place. An area that is currently attracting attention is the Davis Strait which lies between Baffin Island and Greenland. Figure 2 outlines the exploration acreage in the region. Several years of seismic surveys and evaluation have indicated that attractive geological prospects exist. Indeed the geological formations stretching from the Labrador Sea to Baffin Bay appear similar to those of the North Sea where very large reserves have been discovered. With attractive exploration prospects identified, a number of companies with permit acreage in the Davis Strait area are now seeking the necessary approvals to commence drilling operations. A prerequisite to any such approval is the preparation of a comprehensive environmental impact statement on the proposed undertaking and a review and assessment by government regulatory agencies.

PROPOSED DRILLING PROGRAM

Exploratory drilling in Davis Strait is planned for 1979 or 1980. The water depths in the permit area range from about 200 metres to more than 1200 metres.

Drilling will be accomplished using a large drilling vessel, capable of maintaining a stationary position over a well site by utilizing a system referred to as dynamic positioning.

To support a drilling vessel operation, a logistics system is required to move supplies and personnel. Because of the remoteness of the area, a number of supply centres and staging areas will likely be used, including ports in Newfoundland, Baffin Island and Greenland. Transportation will be by support vessel and helicopter to the drillship. The drilling procedure itself will be similar to other conventional offshore operations. As there are presently no drillships in service that have the capability to work in sea ice, the operations will be scheduled for the open-water season and will be restricted towards the end of the season when ice is expected to move into the area. Due to the somewhat adverse physical conditions in the area, a weather and sea ice condition forecasting system will be implemented, including the regular monitoring and tracking of icebergs through a combination of ice reconnaissance flights, shipboard radar and satellite photography. Icebergs that do approach a drillship will be diverted using vessel-towing techniques. In the event the iceberg is too large to tow away, drilling operations will be suspended, the well secured, and the drillship moved off the location until the berg moves past.

Following the completion of a well, the hole will be evaluated, plugged and abandoned. Subsea equipment will be recovered and the rig moved to a new location.

BASELINE GATHERING PROGRAM

In early 1976, a general program was formulated to develop the necessary baseline environmental information that would be included in any submission to government for drilling approval. Throughout the exercise, the overriding concern was with the impact of an uncontrolled blowout of oil extending for a period of time. Other planned activities, however, such as the support operations and routine drilling, required consideration. General government guidelines on the preparation of environmental impact statements were utilized and there was frequent contact with government administrators and scientists regarding the planning and operation of the programs.

Because of its remoteness and inaccessability, the Davis Strait has not been extensively studied by scientists. Early recorded observations were made by whalers and explorers. Some limited fisheries studies have been conducted in the area in conjunction with ICNAF, the International Commission for North Atlantic Fisheries. There is a fairly extensive data base collected by the Danes for Greenland coastal waters. In addition, opportunistic sightings of whales, seals and seabirds have been recorded by people travelling in the area. In order to utilize this information, extensive literature reviews were undertaken in 1976 for the areas where impacts from drilling, specifically an oil blowout, might occur, namely Davis Strait, Hudson Strait, Ungava Bay and the Labrador Coast.

A baseline gathering program commenced in 1976. Sampling was planned for the open water period, and when pack ice was present in the Davis Strait. Thus the choice of vessels was limited by the need for a ship with an ice-reinforced hull. The ship Lady Johnson II out of Newfoundland was hired and has served as the research platform for all subsequent offshore studies. In 1976, oceanographic and biological cruises were undertaken in July, and in early winter (October to December). The data collected in these cruises were preliminary in nature and were intended to help design the large-scale studies planned for 1977 and 1978.

Data were collected utilizing a series of sampling transects spaced approximately 50 km apart along each degree of latitude from 60° N to 67° N.

The 1977 program involved seven cruises covering all seasons to enable determination of seasonal variation, particularly of the biological parameters. Figure 3 shows the sampling grid. Not all stations were occupied during each cruise and during some cruises only limited biological data were collected. During the period of ice cover (approximately November to June), the westward ends of the transects were truncated due to heavy pack ice. The ship was capable of penetrating only a few miles into the ice pack.

Physical oceanographic data on ocean currents were collected using both moored strings of current meters and surface drifter buoys. Salinity-temperature-depth profiling was conducted using either a CTD continuous recording instrument, or discrete depth water bottle salinity determinations coupled with bathythermograph tracing. Ice cover characteristics, ice movements and iceberg frequency were also recorded during appropriate cruises.

Biological data were collected for all trophic levels. Microbiological samples were taken at the surface and a profile was conducted at a station on each transect. These were processed on board the ship and sent to a shore laboratory. Parameters studied included MPN, C-14 labelled glucose uptake and assimilation of crude oil by oleoclasts. This work was conducted by a government scientist during one cruise in 1977 and two cruises in 1978. Phytoplankton was sampled at 6 to 8 depths from surface to 200m using Niskin bottles. The samples were analyzed for total cell numbers and chlorophyl-a. Cell taxonamy was also performed. Nutrient water samples were taken at the same depths as phytoplankton. Analyses were conducted for nitrate/nitrite, phosphate and silicate. Zooplankton and fish egg and larvae were sampled by surface neuston tows and oblique hauls from 200m of a bongo net arrangement. Mesh sizes were 233 and 505 μ. All samples were preserved and taken to a shore laboratory for identification and quantification. Benthic organisms were sampled with a dredge, and identified in the laboratory. The ship was not equipped to sample fish. As a result, only opportunistic data on pelagic and demersal adult fish were collected. In addition, observational data on marine mammals, and marine birds (using the PIROP sighting system) were collected from the ship during every cruise. All of the shipboard sampling and data workup and analysis were conducted for Imperial Oil by MacLaren-Marex, a firm of biological oceanographers.

A series of aerial surveys gathered regional information on the distribution of marine birds and mammals from April through September in 1977. More intensive surveys are being conducted in 1978. The surveys also allowed correlations between bird and mammal distributions and characteristics of ice cover.

A nearshore marine program has investigated various designated shore sites in the study area for distribution and abundance of intertidal and subtidal flora and fauna. In 1978, additional sites are being examined by divers. Also this year, a nearshore fisheries program has been initiated in conjunction with an ongoing government scientific study to collect information on species distribution, abundance, feeding habits and life history in the waters adjacent to Baffin Island. On the northern coast of Labrador, an Arctic char fisheries study is examining the abundance and movement patterns of these fish as they migrate between fresh and marine waters.

Other programs under way in 1978 include a food chain study for the area, utilizing stomach contents of captured fish, birds and mammals; a polar bear study to determine size of the local population, seasonal movements, and feeding areas; and a seal and walrus study to gain information on the ecology of these species along the coast of Baffin Island. The 1978 field programs are intended to fill data deficiencies identified during the 1977 studies.

FATE OF OIL

Concurrent with the collection and analysis of baseline data on the physical and biological environment in the study area, efforts were also underway to predict the outcome of an underwater blowout: that is to determine the fate of released oil in the Davis Strait under varying conditions.

Three situations were considered:

1. A plume of oil and gas particles rising from the sea floor and being dispersed by subsurface and surface currents;

2. Coalescing of the oil particles into a slick at the sea surface, if conditions are calm enough, and then spreading of the slick;

3. The behaviour of oil in pack ice.

Using an oil flow rate of 2500 BBL per day, a sea depth of 500m and a subsurface current of 0.2m/sec., the dispersion model shown in Figure 4 was formulated. The concentration of oil at midwater was calculated to be 12 ppm and at the surface, 3 ppm. This is based on dispersed oil particles of 1.5 mm diameter. At the sea surface, this cloud of dispersed oil would cover an area of approximately 0.05 km^2. In this model, surface turbulence created by wind, waves, and currents will tend to keep the droplets in suspension, and the oil would be carried southeastward with the Labrador Current. After one day, the average oil concentration near the surface in the plume would be 1.3 ppm or one oil particle per 1.4 litres of water. After one week, the plume would contain dispersed oil to a concentration of 75 ppb. Dissolved hydrocarbon levels would be expected to be up to 60 ppb, but only above the blowout site. Downstream levels would approach background.

Under calm conditions, a slick 0.45 mm thick would form above the blowout site. The second model, predicting the movement of this slick model, was the SLIKTRAK program developed by SHELL OIL. The model predicted that after one day, the slick will have moved 18 km downcurrent and have spread to a width of 2 km, with a slick thickness of 0.03 mm. The model predicted that from the proposed drilling sites, in only 4 out of 100 spill situations (during the open water season) would oil reach a shoreline.

The third model considered the movement of oil and pack ice as shown in Figure 5. Oil droplets would be trapped under moving pack ice floes, and thin slicks would form between ice pans and in leads. The dynamic behaviour of moving pack ice would result in oil being deposited on floe edges. The oiled ice would drift southward and a spreading of oiled floes would occur. As the oiled floes moved into warmer waters, and approached the ice edge, thin slicks of oil would be released as the ice melted, and these would be readily dispersed into the water column.

IMPACT ASSESSMENT METHODOLOGY

Based on the biological and physical baseline data and the fate of oil scenarios, the impact assessment was conducted. The proposed activities which were assessed were:

1. Major release of oil from an underwater blowout.
2. Routine drilling operations.
3. Support operations.
4. Oil spill countermeasures.

However, the major concern lay with the potential for a large-scale oil spill.

A methodology was developed around the following components:

1. Identification of biologically important seasons.
2. Preparation of overlay maps showing interaction between environmental components and oil spill scenarios.
3. Development of an impact matrix.
4. Definition of impact magnitude rankings.
5. Review of effect of oil on marine organisms at all trophic levels.
6. Assessment of each interaction between oil and the environment and assignment of rankings.

Using the biological data for the Davis Strait region which had been collected in the field and through literature surveys, five distinct periods, or "seasons", were identified as having significance to impact assessment. By way of example, some of the major factors for each season were:

Late winter:	A large hooded seal whelping patch at the pack ice edge.
	Concentrations of dovekies in light pack ice.
Early spring:	Under-ice flora and associated zooplankton and fish.
	Major spring bloom in northern portion of impact area.

Spring/summer:	Feeding concentrations of phalaropes, fulmars and various larids along ice edge and in leads.
	High zooplankton abundance.
Late summer:	Coastal concentrations of walrus.
	Large breeding concentrations of several species of seabirds and waterfowl.
Fall/winter:	Polar bears feeding on seals at pack ice edge.
	Migrations of several species of seabirds and waterfowl.

The next step was the development of a series of overlay maps for each season. The base map was an outline of the area, in black, with important physical oceanographic parameters added, such as approximate ice edge, and location of the front between the cold north Baffin Current and warm West Greenland Drift, shown in blue. Overlaid onto this were visual presentations of the oil spill scenarios, from various possible well locations marked in brown. Figure 6 shows the fall/winter base map. Then separate overlays were developed using different colours for marine mammals, for birds, for lower organisms (fish, plankton, benthos) and for resource utilization. Each showed the distribution of important species or groups within each trophic level during the specified season. As an example, Figure 7 shows that during fall, walrus hauled out near the ice edge would be impacted by an oil spill from one of the drilling locations. Figure 8 indicates several species of seabirds such as dovekies, fulmar, and gulls to be within the impact area as defined by the oil spill scenarios.

An impact matrix was drawn up, showing interactions between specific species in each of eight groups during the five seasons. Figures 9 and 10 detail the matrix. For each season, three physical habitats were identified. The broad habitat classifications used were: open water, ice and nearshore. The matrix is for only one action, that of an oil well blowout. Its purpose was to identify which species would be vulnerable to effect by an oil spill during specific seasons. The next step was to assess each of these potential interactions.

A review of oil spill effects on marine organisms at all trophic levels was conducted. The review was oriented toward arctic and subarctic species; important groups from temperate regions which relate to or overlap with Davis Strait, Hudson Strait and Labrador Sea populations; and pelagic species. The review included laboratory and field experiments, and observations from a number of incidents.

Definitions were developed to introduce as much objectivity as was possible into the assignment of impact rankings. An impact was defined as:

> "a cause-effect relationship that can be identified or predicted between any facet of the proposed exploratory drilling operation and any flora or fauna in the surrounding environment."

Assigned impacts were ranked as follows: Negligible (0), minor (1), moderate (2), and major (3).

The factors which were considered when assigning a magnitude of impact, or ranking were:

1. Population size and geographic extent.
2. Susceptibility to oil.
3. Percent of population likely to be affected.
4. Potential for recovery of the population by reproduction and immigration.
5. Uniqueness of the population.
6. Importance to humans.

The four levels of impact were defined as follows:

A Major Impact is that affecting a whole population or species in sufficient magnitude to cause a decline in abundance and/or a change in distribution beyond which natural recruitment (reproduction and immigration from unaffected areas) would not return that population or species, or any population or species dependent upon it, to its former level within several generations. A major impact may also be classified as that affecting a subsistence or commercial use, such that the wellbeing of the user is affected over a long term.

A Moderate Impact is that affecting a portion of a population which may result in a change in abundance and/or distribution over one or more generations of that portion of the population or any population dependent upon it, but which does not change the integrity of any population as a whole. A short-term effect on the wellbeing of those who utilize the resources also constitutes a moderate impact.

A Minor Impact is that affecting a specific group of individuals of a population at a localized area and/or over a short time period (one generation or less), but which does not affect other trophic levels or the integrity of the population itself.

Any impacts below the minor category are considered Negligible.

These definitions result in impacts being considered at the individual and population level. While a formal attempt to look at the community level was not made, the consequences of an oil spill on trophic interactions were considered.

Utilizing this methodology, an environmental assessment was undertaken, using data collected during 1976 and 1977, plus other published literature and historical documentation. Two examples of assessments which resulted in assignment of a major impact rating are given below. These are taken from Figure 9.

The Hooded Seal congregates in March in distinct whelping patches that have been observed from aerial surveys. As many as 30,000 pups may be born at this time on the pack ice and along the edge. This may represent a major source of recruitment of hooded seals for the population of the region. The females and newborn pups are in a stressful life stage at this period of time and any additional stress caused by contact with oil could result in death due to physiological or behavioural changes. Thus, because of the vulnerable period of life, and the large, congregated numbers of animals, the magnitude of impact is considered major.

Polar Bears frequent the pack ice and ice edge, and at times are congregated around seal patches. During March, a portion of the region's population appears to be associated with the hooded seal whelping patches. At this time of year the bears may be using the whelping patches as a food source to sustain them through that period of the winter when other food sources, such as harp seals, are limited and widely scattered. If this food source was reduced or the hunting potential affected by the presence of oil between or on floes, a number of animals could die from starvation. Although little is known about effects on polar bears from direct oiling, contact with oil might cause thermoregulatory disturbance in bears. Thus, the magnitude of the impact is considered to be major, as the population in the region is believed to be small, and a portion of that population could be affected.

Similar assessments were made for other mammal species, birds, fish and lower trophic levels. In total, 1500 individual assessments were considered, of which six were classified as major, involving four different species at various times of the year. 55 moderate impacts were identified, and 149 minor impacts, the remainder being negligible. It is highly unlikely that all impacts which were identified could occur in any one particular oil spill. The number would depend on various circumstances, including the season, amount of oil and spill trajectory. However, the assessment does serve to indicate the "worst case" situation.

CONCLUSIONS

As part of the requirements for drilling approval, an environmental impact statement was prepared in late 1977 for submission to government. The statement itself, some 250 pages, includes a description of the proposed drilling program, a review of the present environment, both physical and biological, a section on resource utilization, the impact assessment for a blowout and other activities, a section on contingency planning, and residual impacts. In addition, all technical and backup documents and reports were made available with the statement. The reports were reviewed by various agencies within the Canadian Government through a standard environmental review process. In addition, public hearings will take place in northern communities in the fall of 1978. Based on the recommendations coming from this review process, along with the continuing environmental studies being conducted this year, decisions will be made regarding drilling approval, and the conditions and restraints attached to any approval.

OFFSHORE EXPLORATION REGIONS OF CANADA

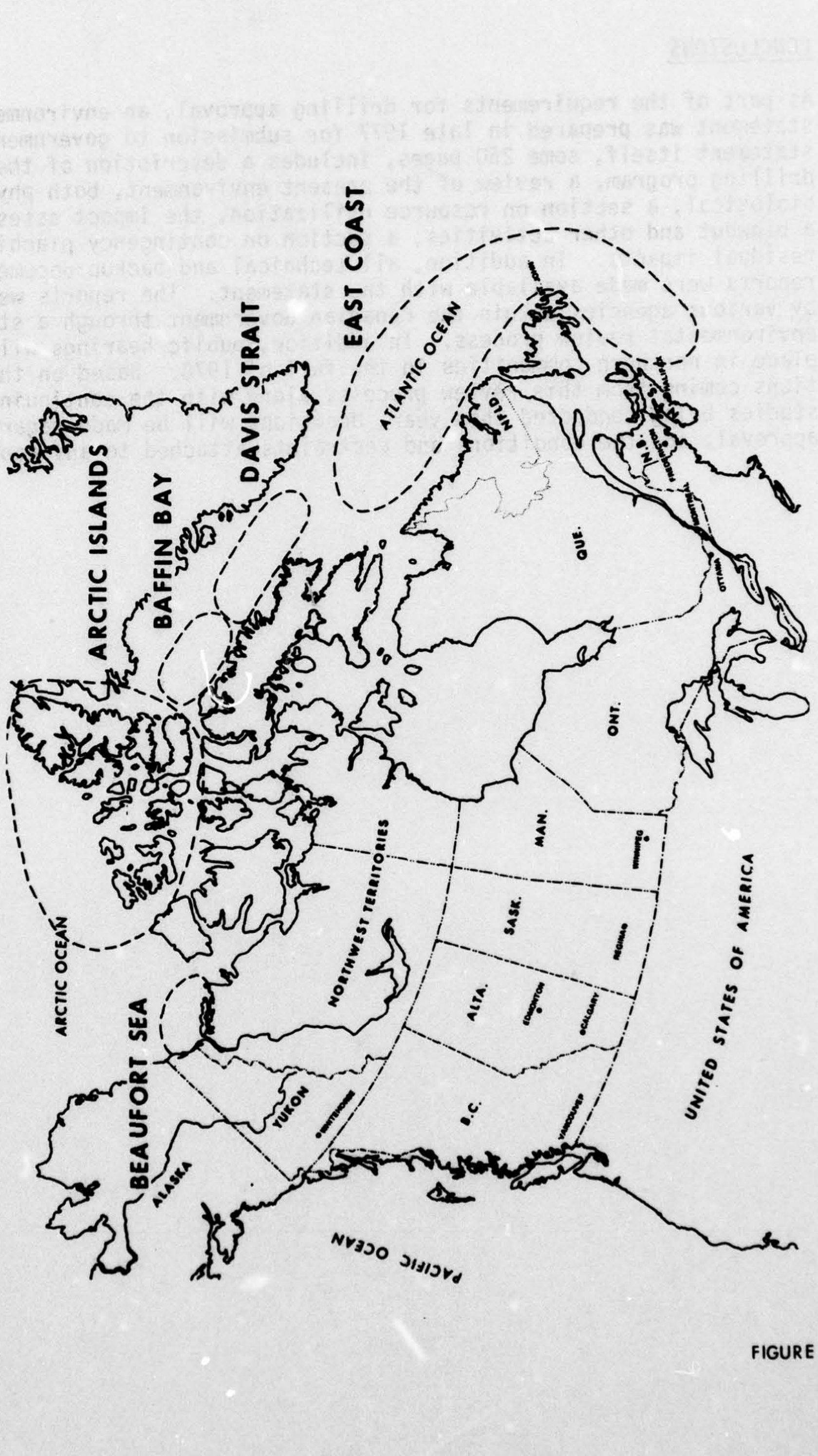
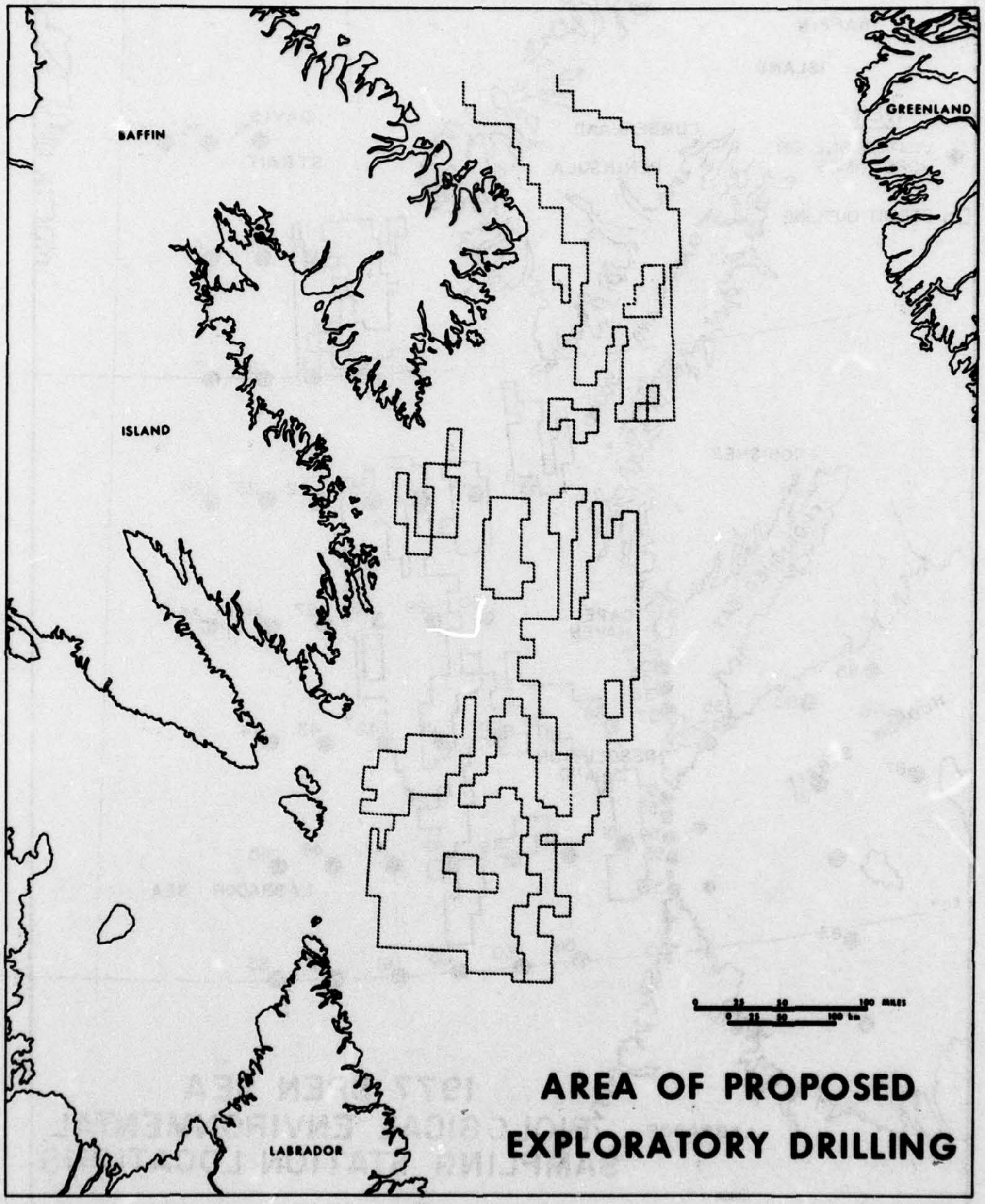


FIGURE 1



AREA OF PROPOSED EXPLORATORY DRILLING

FIGURE 2

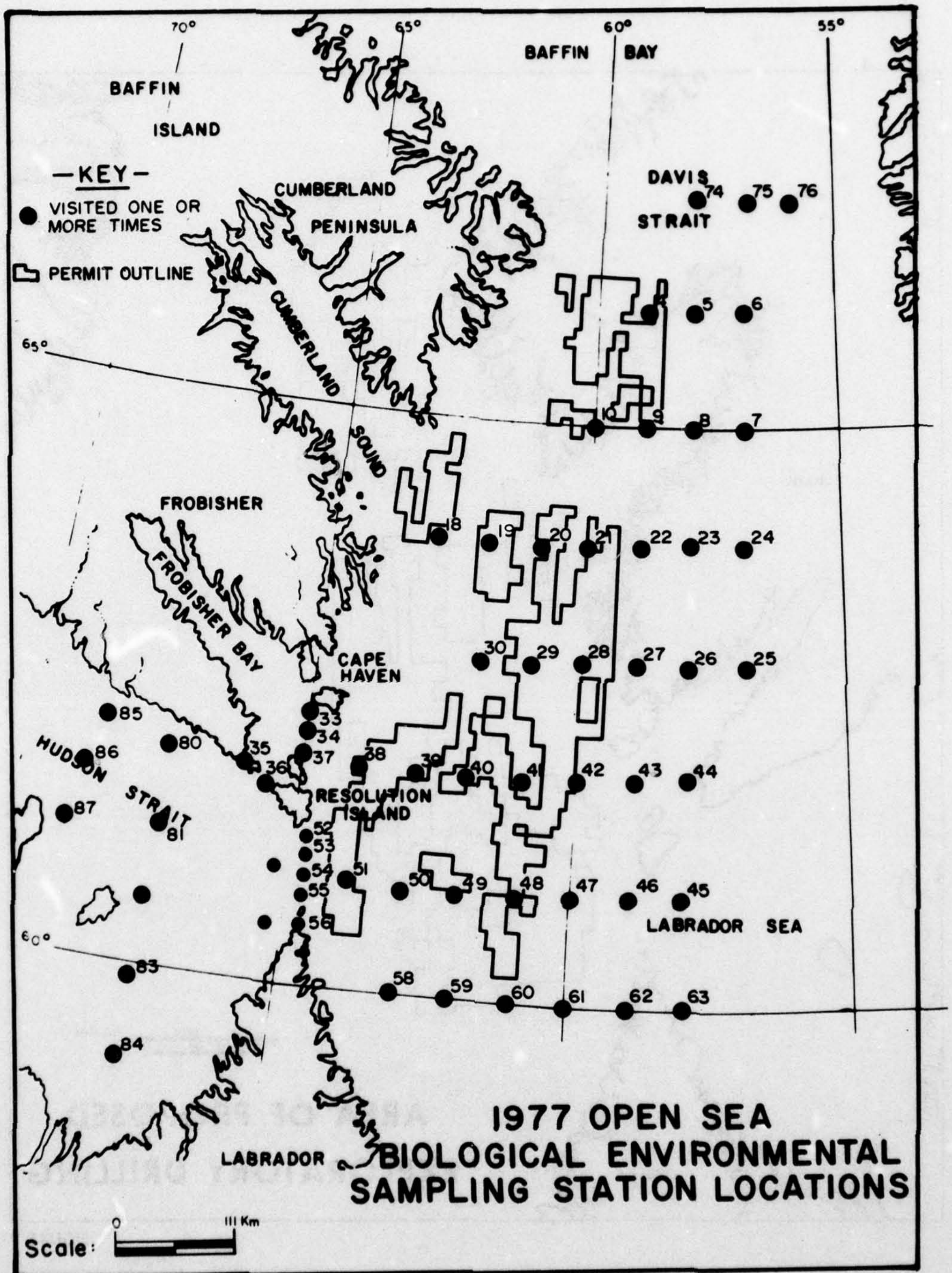

70°
65°
60°
55°
65°
60°
BAFFIN BAY
BAFFIN
ISLAND
-KEY-
VISITED ONE OR MORE TIMES
PERMIT OUTLINE
CUMBERLAND
PENINSULA
DAVIS
STRAIT
CUMBERLAND
SOUND
FROBISHER
FROBISHER BAY
CAPE HAVEN
HUDSON STRAIT
RESOLUTION ISLAND
LABRADOR SEA
LABRADOR
1977 OPEN SEA
BIOLOGICAL ENVIRONMENTAL
SAMPLING STATION LOCATIONS
Scale: 0 111 Km
74 75 76
5 6
10 9 8 7
18 19 20 21 22 23 24
30 29 28 27 26 25
85 86 80 33 34 35 36 37 38 39 40 41 42 43 44
87 81
52 53 54 55 56 51 50 49 48 47 46 45
83 58 59 60 61 62 63
84

FIGURE 3

PLUME CONFIGURATION OF OIL DROPLETS
(1–2 mm DIAMETER)

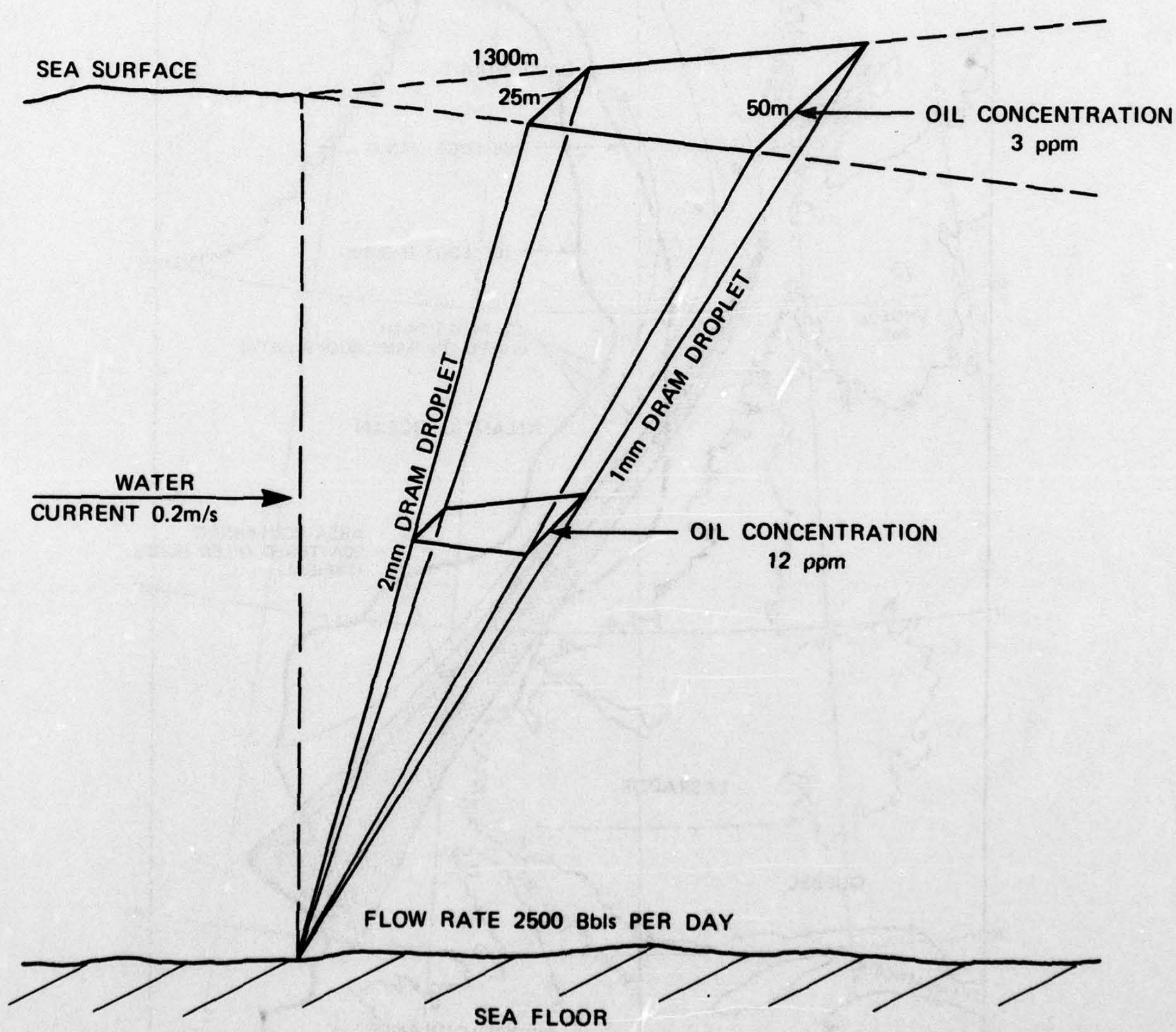
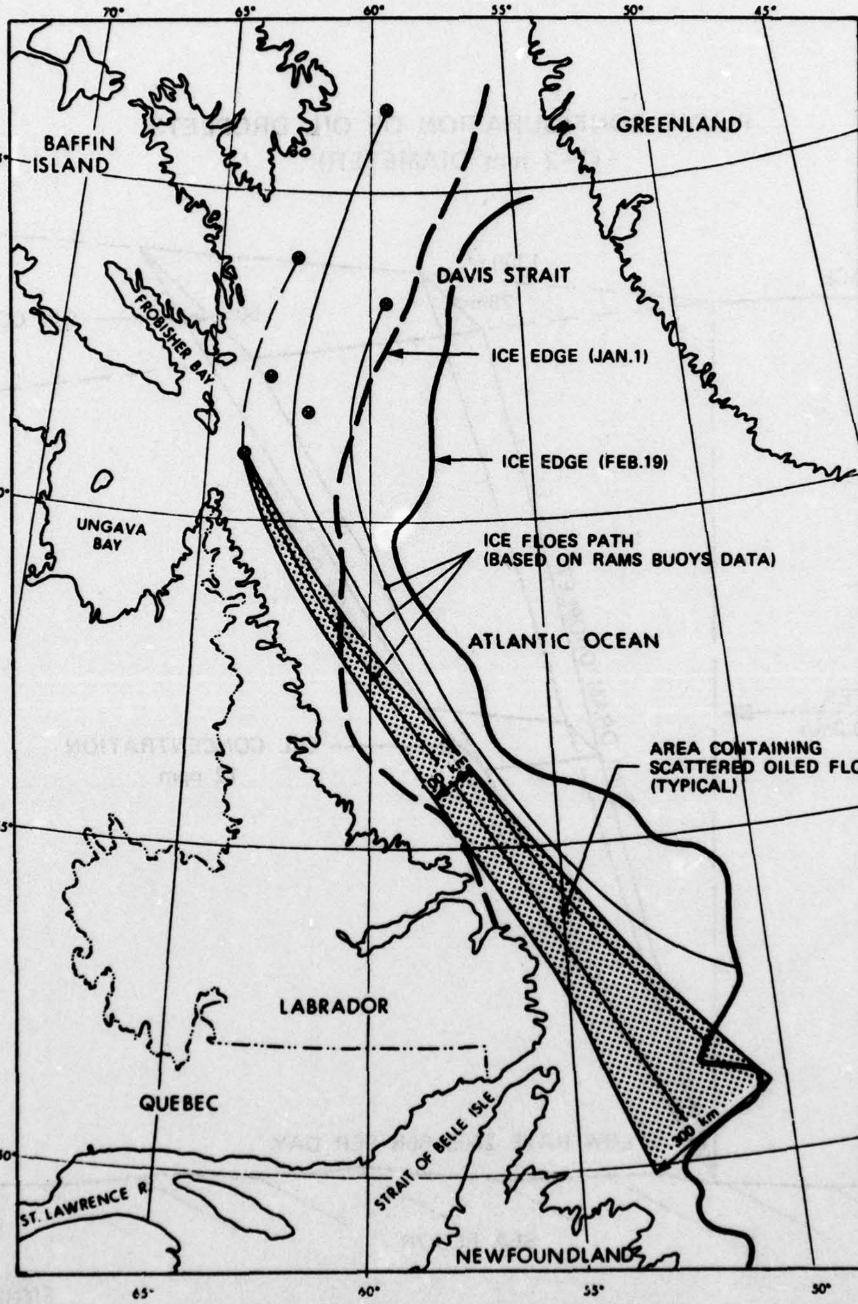


FIGURE 4

OILED FLOES TRAJECTORIES



● LOCATIONS CHOSEN FOR SLIKTRAK SIMULATIONS

FIGURE 5

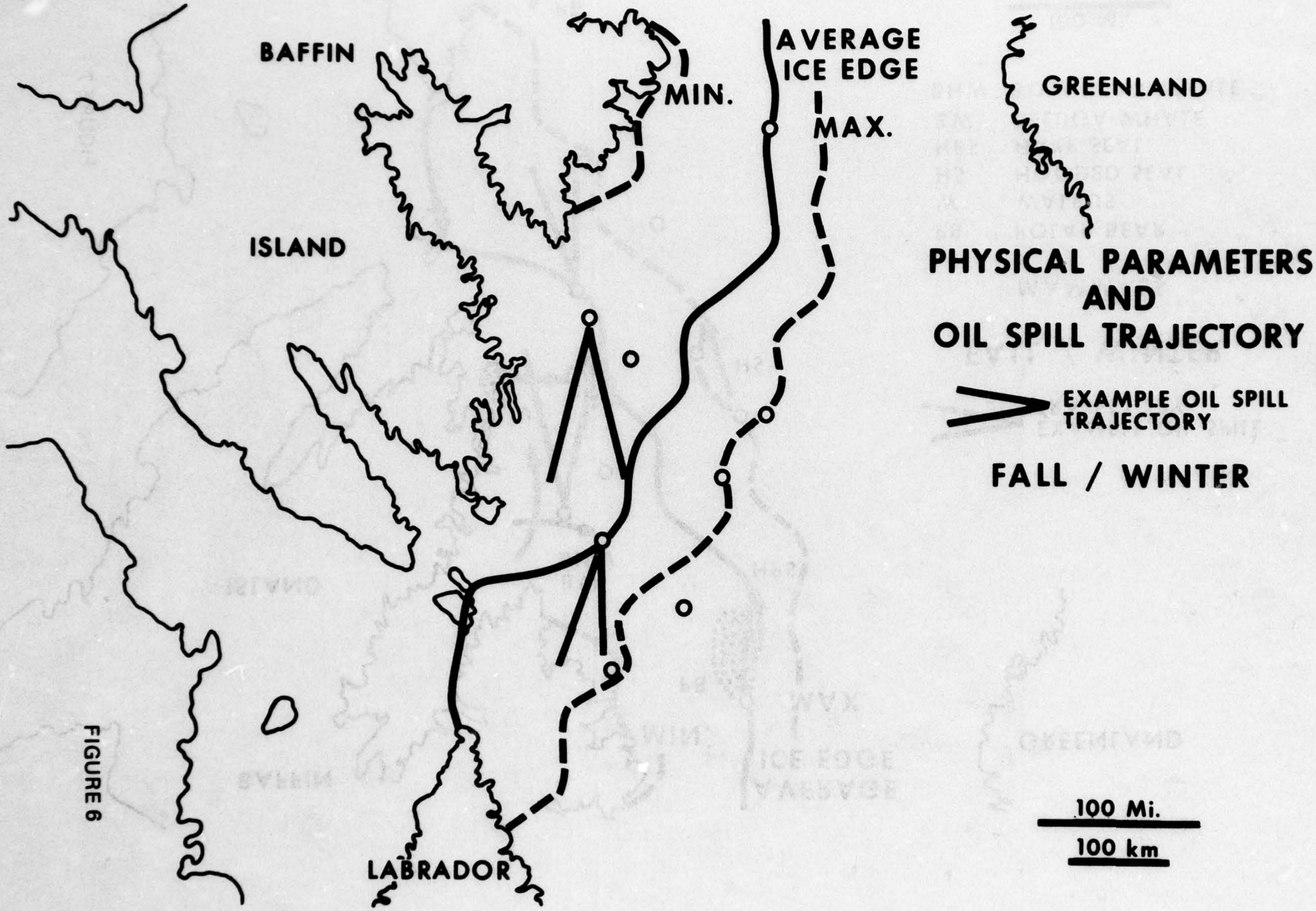

BAFFIN
ISLAND
AVERAGE
ICE EDGE
MIN.
MAX.
GREENLAND
PHYSICAL PARAMETERS
AND
OIL SPILL TRAJECTORY
EXAMPLE OIL SPILL
TRAJECTORY
FALL / WINTER
100 Mi.
100 km
LABRADOR

FIGURE 6

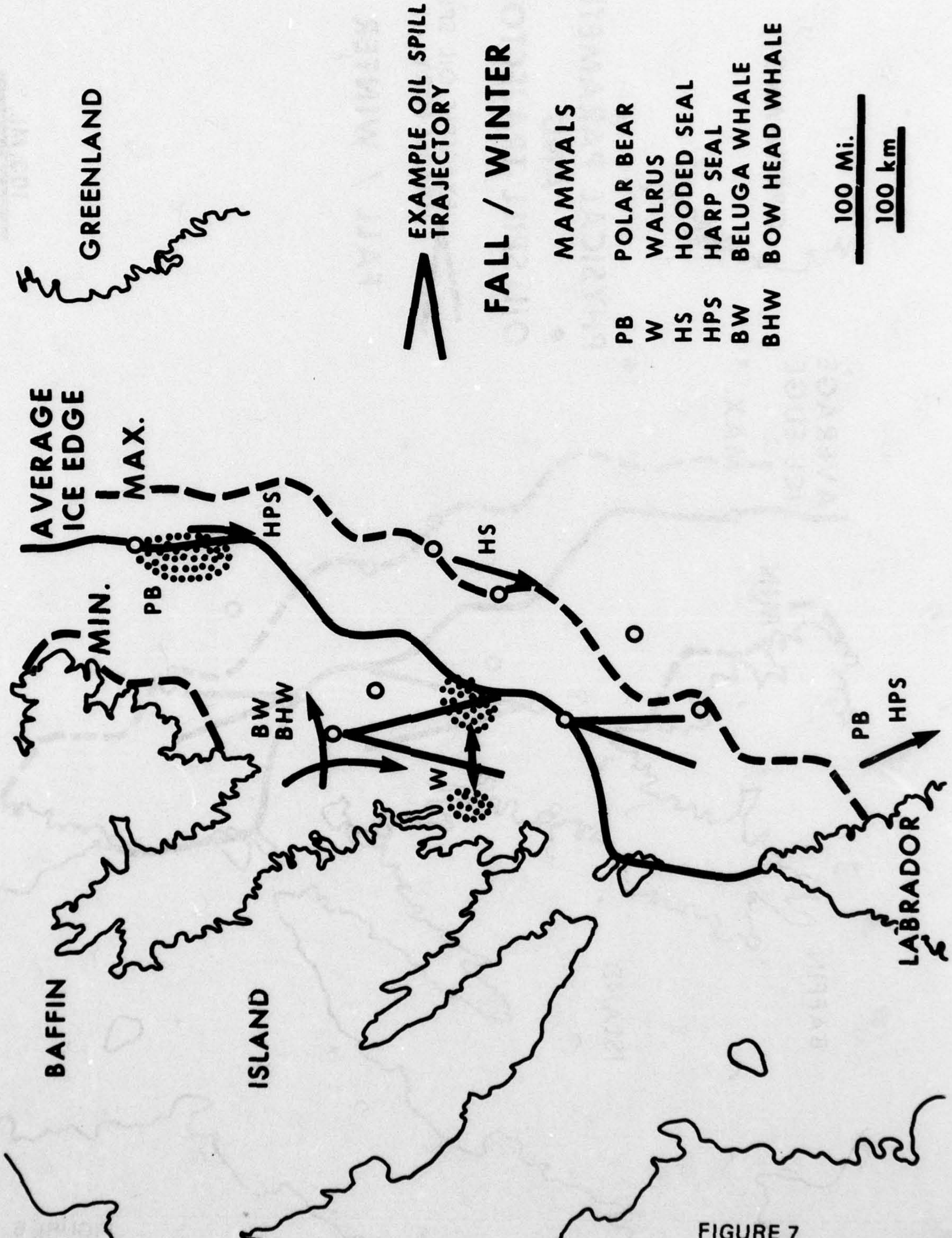

AVERAGE ICE EDGE
MIN.
MAX.
GREENLAND
BAFFIN
ISLAND
LABRADOR
PB
HPS
HS
BW
BHW
W
PB
HPS
EXAMPLE OIL SPILL TRAJECTORY
FALL / WINTER
MAMMALS
PB POLAR BEAR
W WALRUS
HS HOODED SEAL
HPS HARP SEAL
BW BELUGA WHALE
BHW BOW HEAD WHALE
100 Mi.
100 km

FIGURE 7

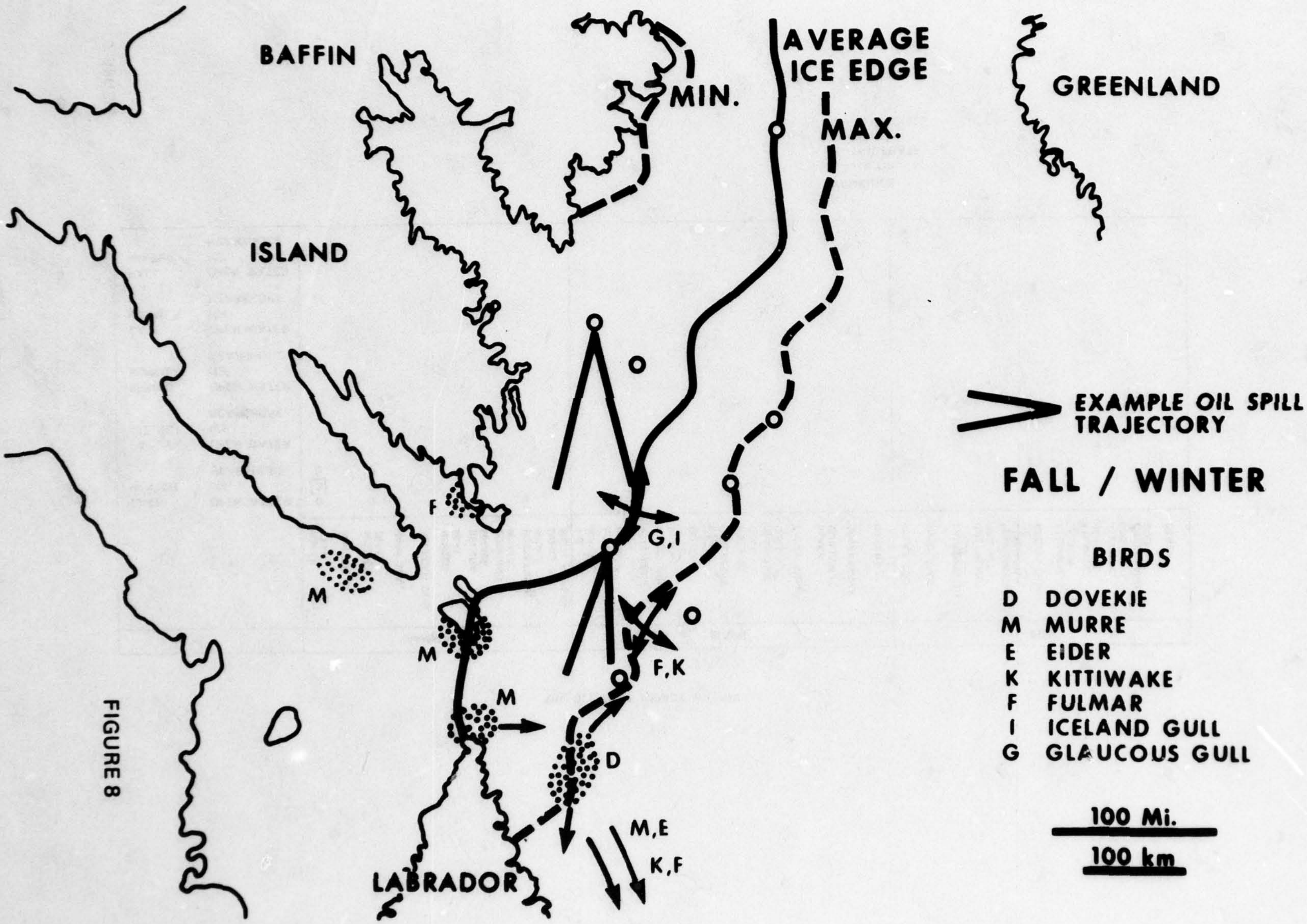

BAFFIN
ISLAND
MIN.
AVERAGE
ICE EDGE
MAX.
GREENLAND
G,I
F,K
F
M
M
M
D
M,E
K,F
LABRADOR
EXAMPLE OIL SPILL
TRAJECTORY
FALL / WINTER
BIRDS
D DOVEKIE
M MURRE
E EIDER
K KITTIWAKE
F FULMAR
I ICELAND GULL
G GLAUCOUS GULL
100 Mi.
100 km

FIGURE 8

OIL BLOWOUT IMPACT MATRIX

		MAMMALS										BIRDS												FISH										
		POLAR BEAR	WALRUS	HOODED SEAL	HARP SEAL	BEARDED SEAL	RINGED SEAL	BELUGA WHALE	BOWHEAD WHALE	BOTTLENOSE WHALE	MINKE & PILOT WHALES	T.B. MURRE	NORTHERN FULMAR	B.L. KITTIWAKE	N. COMMON EIDER	DOVEKIE	RED PHALAROPE	ICELAND GULL	GLAUCOUS GULL	IVORY GULL	BLACK GUILLEMOT	SHEARWATER	OTHER	POLAR COD	SANDLANCE	LANTERNFISH	GREENLAND HALIBUT	ROUNDNOSE GRENADIER	ARCTIC CHAR	ATLANTIC SALMON	ATLANTIC HERRING	ATLANTIC COD	GREENLAND COD	OTHER
LATE WINTER	OPEN WATER	0		0																														
	ICE	$\boxed{3}$		3																														
	NEARSHORE	0		0																														
EARLY SPRING	OPEN WATER																																	
	ICE																																	
	NEARSHORE																																	
SPRING SUMMER	OPEN WATER																																	
	ICE																																	
	NEARSHORE																																	
LATE SUMMER	OPEN WATER																																	
	ICE																																	
	NEARSHORE																																	
FALL WINTER	OPEN WATER																																	
	ICE																																	
	NEARSHORE																																	

RANKINGS
3 – MAJOR
2 – MODERATE
1 – MINOR
0 – NEGLIGIBLE

FIGURE 9

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THE PROCEEDINGS OF THE CONFERENCE ON ASSESSMENT OF ECOLOGICAL I--ETC(U)
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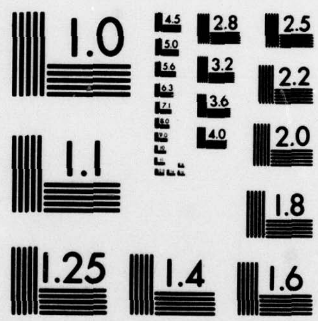

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

OIL BLOWOUT IMPACT MATRIX

LOWER TROPHIC LEVELS

		ZOOBENTHOS							ZOOPLANKTON				MACRO-PHYTES		MICRO-ALGAE		MICRO-BIOTA	
		DECAPODS	MOLLUSCS	AMPHIPODS	POLYCHAETES	BARNACLES	GASTROPODS	OTHER	COPEPODS	SHRIMP (PANDALUS)	MEROPLANKTON	AMPHIPODS & EUPHAUSIIDS	SUBLITTORAL	LITTORAL	PHYTOPLANKTON	ICE FLORA	OLEOCLASTS	NON-OLEOCLASTS
LATE WINTER	OPEN WATER																	
	ICE																	
	NEARSHORE																	
EARLY SPRING	OPEN WATER																	
	ICE																	
	NEARSHORE																	
SPRING/ SUMMER	OPEN WATER																	
	ICE																	
	NEARSHORE																	
LATE SUMMER	OPEN WATER																	
	ICE																	
	NEARSHORE																	
FALL/ WINTER	OPEN WATER																	
	ICE																	
	NEARSHORE																	

RANKINGS

3 – MAJOR
2 – MODERATE
1 – MINOR
0 – NEGLIGIBLE

FIGURE 10

POTENTIAL LONG-TERM EFFECTS OF PRUDHOE BAY CRUDE OIL IN ARCTIC SEDIMENTS ON INDIGENOUS BENTHIC INVERTEBRATE COMMUNITIES

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ABSTRACT

Laboratory and field experiments were performed to determine the potential toxicity of Prudhoe Bay crude oil to indigenous Arctic benthic invertebrates. Toxicity was measured as mortality and as sublethal behavioral changes in feeding, movement and burrowing activities. When sediment was contaminated with fresh Prudhoe Bay crude oil, burrowing activity of the amphipod *Boeckosimus* (=*Onisimus*) *affinis* was significantly reduced. Weathering of the oil was monitored by gas-liquid chromatography. Given a choice, in laboratory studies with oil contaminated or uncontaminated sediment, the amphipods selectively burrowed into the uncontaminated sediment. Exposure in experimental chambers to sediment contaminated with fresh oil also resulted in decreased movement and feeding activity during the month that the oil underwent initial weathering. Mortality rates were low for amphipods exposed to sediment contaminated with fresh or weathered oil. Behavioral changes in feeding and movement appear to be temporary and associated with the light hydrocarbons present in fresh crude oil. Inhibition of burrowing activities persisted beyond the time of initial oil weathering.

Recolonization of *in situ* oil-contaminated sediment was monitored for 30 weeks. Amounts of residual oil were quantified using spectrofluorometric methods. Recolonization began within two weeks of oil contamination. The benthic community recolonizing oil contaminated areas was significantly different in species composition from that in unoiled reference areas. Isopods did not appear to be attracted or repelled by the oil. Depending on the species, polychaetes were either attracted or repelled by the oil. Amphipods avoided recolonizing oil contaminated areas. The preference for burrowing in unoiled substrate shown in the laboratory studies appears to be reflected in the avoidance of oil contaminated sediment in the *in situ* Arctic benthic community studies.

INTRODUCTION

The exploitation of oil reserves in Alaska subjects its waters to an increasing probability of contamination by petroleum hydrocarbons. A study done for the U. S. Coast Guard (Battelle Northwest, 1973) concluded that ". . . practically every mile of the coastline of mainland Alaska will be subject to oil spills" by the mid-1980's. A joint Federal-State lease sale for oil and gas development in the Beaufort Sea is scheduled in December, 1979, for an area from the Colville to the Canning Rivers. Canadian activity in the Arctic has been centered offshore near the MacKenzie Delta.

An understanding of ecosystems petroleum pollutants can contaminate and what organisms may come in contact with polluting hydrocarbons is essential to a meaningful toxicology study. McAuliffe (1977) has pointed out that many bioassay tests are "unrealistic" as they do not occur under conditions reflecting hydrocarbons in the environment. The present study examines the effects of sediment bound oil on benthic invertebrates.

Oil from a spill can be expected to enter the sediments (Blumer, *et al.*, 1971; Blumer and Sass, 1972; Conover, 1971; Drake, *et al.*, 1971; Kolpack, *et al.*, 1971; McAuliffe, *et al.*, 1975). Biological as well as chemical and physical factors can move oil spilled on the surface into sediment. In the Arctic transport of oil from offshore wells will likely be through buried pipelines. Breaks in these pipelines will directly contaminate sediment and benthic communities. Thus, oil may contact benthic organisms.

Amphipods were chosen as the principal bioassay organisms for these studies because of their abundance and overall distribution in Arctic marine ecosystems, and their importance in the food web. The abundance and distribution of amphipods in the area has been well documented (Alverson and Wilmovsky, 1966; MacGinitie, 1955; Sparks and Pereyra, 1966). The advantages of using benthic organisms in pollutant studies have been summarized by Cairns and Dickson (1971), Goodnight (1973), Hynes (1974), and Wilhm and Dorris (1973). Amphipods are important members of arctic food webs. Amphipods have been reported to be important sources of food for ringed seal (Lowry, 1977; Johnson, *et al.*, 1966), bowhead whale (Patee, personal communication; Mitchell, 1975), arctic fishes (Craig and McCart, 1976; Griffiths, *et al.*, 1975; Tillman, 1975) and birds in the arctic (Schwartz, 1966; Pethon, 1967; Kistchinski and Chernov, 1973; Witherby, *et al.*, 1952).

MATERIALS AND METHODS

The benthic amphipod *Boeckosimus* (=*Onisimus*) *affinis* (Hansen) was selected for laboratory studies of effects of oil in sediment. The species is abundant near Point Barrow, and its habitat, a shallow marine lagoon, comprises 60% of the Alaskan coast from Point Barrow to the Canadian border (Lewellen, 1973). Sites of capture of *Boeckosimus affinis* and the *in situ* experiments were in Elson lagoon, 50 m and 250 m, respectively, south of Plover Point, approximately six miles east of Barrow, Alaska. Experimental animals were captured in baited

wire mesh traps, and shipped to Louisville, Kentucky. Animals were maintained at 5°C and 27‰ salinity during shipping, and were allowed to acclimate for two weeks before any experiments were begun.

Oil contaminated sediment for *in vitro* studies was prepared by mixing 500 ml of either fresh Prudhoe crude oil or weathered Prudhoe crude oil with 2500 g of clean sandy sediment. Oil was weathered by heating to 30°C under a vacuum for 25 hours.

After mixing, the oiled sand was allowed to stand for 96 hours. After this time it was thoroughly rinsed with water and placed in trays. Trays, 36 cm x 17 cm, were filled with sediment to a depth of 4 cm. Trays were overlain with 5 l artificial seawater (Instant Ocean). Trays were established so that 100% of the sediment surface was treated with fresh-oil or weathered-oil, 50% of the sediment surface was oiled and 50% was clean, or 100% of sediment was clean. All situations were run in duplicate. Overlying water was replaced every two weeks with fresh seawater.

A total of 60 amphipods, each 13-16 mm in total length, were exposed to each oiled sediment situation.

Mortality and general activity were checked daily for *in vitro* tests. Organisms that appeared dead, i.e., lacked pleopod movement and failed to respond to touch were removed to separate chambers and observed for an additional 24 hours. No recovery was ever noted. The necessity of this post-exposure observation has been demonstrated by Hansen and Kawatski (1976).

Movement was measured in an open field apparatus, a square glass tray 50 cm on a side and ten cm deep, with a grid marked on the bottom. The grid was composed of 100 squares, each five cm on a side. Each square was identified by a letter and a number, e.g., A3, L6. The tray was filled with clean water and five animals were introduced. After ten minutes acclimation each animal was given a gentle touch with a glass rod. As the animal moved, the grid square it occupied was noted every five seconds for three minutes. For quantitative purposes an animal was assumed to always be in the center of a square at the time of recording, and to travel in a straight line between squares. The distance traveled for each five-second interval was then determined and expressed as units of movement (units of movement x 5 = cm moved).

The ability to find and recognize food was measured in a glass tray, similar to the open field tray. Animals were placed in the tray and after ten minutes acclimation, a cube of clean (not oil-tainted) fish, approximately two cm on a side, was placed in the middle of the tray. The number of animals feeding was noted at ten minute intervals for one hour. Animals had not been offered food for ten days prior to these tests.

At times of water change, the sediments in the *in vitro* trays were slowly turned over with a glass rod, causing the burrowing amphipods to emerge. Numbers of animals on the sediment surface and numbers of burrowing amphipods were recorded.

For *in situ* studies, sediment was collected from Elson Lagoon by scuba divers. The sediment was a silty clay. Animals were removed from the sediment by hand picking and screening (mesh size 4 mm). Two hundred ml of Prudhoe crude oil were poured into Plexiglas trays 25 cm x 25 cm x 7 cm. Sediment was placed on top of the oil until the tray was filled. Control

trays were handled identically, except no oil was added. Each tray was fitted with a Plexiglas top, lowered to the bottom, and moved by divers to the study site. Trays were placed in rows of six, with a pattern of one control tray, two oiled trays, one control tray, and two oiled trays per row. Approximately 50 cm was left between trays. Fifteen rows were placed on the ocean bottom and after the trays were in place the tops were removed.

At intervals of 1, 2, 3, 4, 8, and 30 weeks, six trays, the four oiled and two control trays of a single row, were recovered. Divers replaced the Plexiglas tops before moving the trays.

All sediment was run through a U. S. Standard sieve of four mm hole diameter for the first two sets of trays. No invertebrates were found below four cm, at which point the sediment appeared to be anaerobic. Because of the total absence of invertebrates below 4 cm, only the surface four cm of sediment were examined for the remaining trays. All recovered animals were rinsed of oil in a container of ether, and the oil returned to the sediment. Animals were preserved in 10% buffered formalin and identified. Identifications were confirmed by Helmut Koch of Western Washington University and George Mueller and Kenneth Coyle of the University of Alaska.

Samples of sediment from *in vitro* studies were collected before each water change, and subjected to analysis by gas-liquid chromatography, using a Hewlett-Packard (Palo Alto, CA) Model 5830A with a dual-flame ionization detector. Sediment portions (approximately 10 g dry weight) were extracted with 250 ml of diethyl either in a Soxhlett extractor and concentrated to 2 ml. One µl was injected into a 3 m x 3 mm column packed with 3% OV-1 on Supelcoport 80-100 mesh (Supelco, Inc.). Temperature was programmed at 40°C isothermal for three minutes, at 8°C per minute to 250°C, and held isothermal at 250°C for 40 minutes.

Oil content of *in situ* sediment was determined with an AMINCO Model SPF-125 spectrofluorometer, using the methods described by Keizer and Gordon (1973) and Gordon, *et al.* (1974). A subsample of 25 g of sediment was placed in a 250 ml beaker with 30 ml of water and 30 ml of spectrofluorometric grade methylene chloride. The beakers were placed on a rotary shaker, and the contents mixed overnight at 200 rpm. The mixture was filtered to remove sediment, and a separatory funnel utilized to remove water. Methylene chloride was removed under gentle vacuum at 30°C in a rotary evaporator. The recovered oil was resuspended in hexane. Fluorescence was determined immediately after dissolution in hexane. Excitation wavelength was 405 nm, and emmission was read at a wavelength of 450 nm. Scans throughout the range of oil fluorescence were made to determine these points of maximum value. Oil concentrations were determined from calibration curves prepared from whole oil. Data was analysed for statistical significance by two way analyses of variance (Sokal and Rohlf, 1969). The use of the term "significant" throughout this paper refers to a probability of exceeding F of greater than $\alpha=0.05$.

RESULTS

In Vitro Experiments

Measurement of Oil in the Sediment

Gas liquid chromatography of the oil from the *in vitro* sediments showed a reduction in the quantity of C_{13} and lighter hydrocarbons with time from sediments contaminated with fresh crude oil. No such change occurred in analyses of oil from sediments contaminated with oil that had been weathered. Significant biodegradation of compounds of higher molecular weight compounds was not detected.

Survival

The survival rate of control animals decreased only slightly throughout the experiment, with 90% of the animals still alive at the end of the fourteen week experiment (Table 1). Animals in trays of sediment treated with fresh crude oil showed a decrease in survival rate to 85% after four weeks, and decreased slightly to 76%-82% survival through the remaining ten weeks. In the weathered oil situations, the first four weeks of exposure produced a reduction to 90%-96%. During the remaining time survival was reduced only to 84%-90%. This was an average of 8% higher than in the fresh oil situations, and only 3% lower than that of the control animals.

Food Search/Recognition Success

Over 90% of the control animals located food and were feeding during all trials throughout the experiment (Table 2). Of the amphipods exposed to sediments with 50% or 100% of the surface area contaminated with fresh oil, only 24% and 36% of the animals fed successfully after two weeks exposure; only 55% and 65% were successful after four weeks exposure. After four weeks the rate increased to 8% or more during the remaining time of the experiment. Animals exposed to sediment in which 100% of the surface area was contaminated with weathered oil showed 68% success in food search and recognition after two weeks. This was roughly twice the success rate of animals on sediment contaminated with fresh oil. A similar pattern was shown throughout the remainder of the experiment, with 60% success after four weeks, and a better than 90% success in the remaining trials. Animals exposed to sediment with its surface 50% contaminated with weathered oil showed a success rate very close to that of the control situation, with better than 89% of the amphipods feeding successfully at all trials.

Burrowing and Sediment Preference

In control trays 80% of the amphipods burrowed in the sediment after two weeks exposure, and they maintained a burrowing rate of 85% or higher throughout the experiment, with the exception of only a slight decrease after eight weeks (Table 3). Inhabitants of trays with 100% of the sediment contaminated with fresh oil exhibited a burrowing rate of only 24%

after two weeks and 19% after four weeks of exposure. This rate increased to 51% after six weeks and fluctuated between 50% and 60% for the remainder of the experiment. Given a choice of clean sediment or fresh-oiled sediment 43% of the amphipods burrowed in clean sediment compared to only 17% utilizing the contaminated sediment after two weeks exposure. For the following six weeks the amphipods used clean and contaminated substrates about equally, but after ten weeks the preference for clean sediment over contaminated sediment rose to approximately two to one. No consistent pattern of sediment preference for animals lying on top of the substrate was exhibited. Although animals showed preferences for burrowing, animals that did not burrow, but lay on the surface of the sediment, showed no preferences among clean, fresh-oiled, and weathered-oiled sediments.

Animals exposed to sediment with its entire surface contaminated with weathered oil exhibited a similar response to those exposed to totally fresh-oiled substrates for the first four weeks, with approximately one-fourth of the animals burrowing. After this time, however, the burrowing rate in weathered sediments decreased to a maximum of 11% for the duration of the study, with 90% of the animals preferring to live on the substrate as opposed to burrowing. This is in direct contrast to the 100% fresh-oiled sediment situation, which exhibited an increase in burrowing after four weeks.

Given a choice of weathered-oil contaminated sediment or clean sediment 85% of the animals chose clean sediment with only 9% selecting contaminated substrate after two weeks exposure. This preference for clean sediment slowly decreased to approximately 50% of the animals present while utilization of contaminated sediment slowly rose to a maximum of 42%. In contrast to the totally contaminated weathered-oil situations, no large increase in the numbers of animals preferring to lie on the substrate occurred, although more animals did lie on top during the fourth through eighth weeks than did before or after this interval.

Movement

The distance moved and the time during which movement occurred (expressed as a percent of total time observed) are presented in Tables 4 and 5. All oil treatments significantly lowered total distance moved and reduced the time during which movement was observed (Table 6).

Animals exposed to sediments containing fresh oil exhibited a significant decrease in movement as a result of the interaction of treatment and time. A two-way ANOVA showed this decrease to be significant at the .01 level.

No significant corresponding effects on movement were caused by the interaction of exposure to sediment containing weathered oil and time exposed. Effects of exposure to substrate containing weathered oil were manifested from the first measurements, after two weeks, and these effects neither increased nor decreased significantly with longer exposure to the weathered oil.

In Situ Experiments

Measurement of Oil in the Sediment

Measurements of oil in *in situ* sediments are shown in Table 7. With the exception of the first week's samples, the weekly means are very similar. Although some of the lighter fractions of the oil may have moved into the water column, the bulk of the oil remained in the sediment throughout the study period.

Recolonization

Species and numbers of animals recolonizing the control and oiled trays are given in Table 8. Of all the taxa represented, the amphipods exhibited the most uniform and dramatic choice in habitat. Although several of the species were not present during the first month of the study, they overwhelmingly preferred clean sediments after eight and thirty weeks.

No clear pattern of substrate choice was found for the isopods. Observations by divers noted the larger isopod, *Saduria entomon*, crawled in and out of oiled and control trays during all times the divers were present. The species appeared neither attracted nor repulsed by the presence of oil.

Polychaetes did not respond uniformly to the presence of oil. Of the species occurring more than rarely, *Pectinaria granulata* and *Scolopolos armiger* showed a clear preference for clean sediment throughout the experiment. The *Nephytes* sp. was found only in association with oil in the two instances in which it was present. *Capitella capitata* did not occur until after thirty weeks, but showed a preference for clean substrate at that time.

As a group the mollusks preferred clean sediment, with *Admete* showing no real preference at the one time interval in which it occurred. Despite divers' notes on the relative abundance of gastropods in the area, none were found in any trays, clean or oiled, except after thirty weeks.

DISCUSSION

Little has been known about the effects of oil-contaminated sediment on Arctic benthic forms (Clark and Finley, 1977). The present experiments showed that exposure to oiled sediment reduced the survival rate but did not result in major mortality. The difference observed (8%) between mortalities with exposure to fresh oil and weathered oil implicates the lower boiling compounds of the oil, which are lost by weathering, as the toxic components resulting in mortality. This has been previously postulated (McAuliffe, 1977; Moore and Dwyer, 1974).

The lack of difference in mortality between situations in which one-half of the surface of the sediment was contaminated and the entire surface was contaminated may indicate that constant exposure to the oiled sediment is not necessary to cause mortality. The mortality might not be caused by the oil in the sediment, but by soluble components leaching into the water column. The movement of animals would be sufficient to mix these components throughout the water column.

The ability of *Boeckosimus* to locate food and then to feed was markedly

reduced during the first four week of their exposure to substrate contaminated with fresh oil. Compared to control animals after two and four weeks of exposure only 40% of the amphipods exposed to fresh oil were able to find food and feed during these periods. The success rate when weathered-oil covered the whole sediment surface was nearly twice this rate. After the amphipods' initially depressed feeding, success rates rose throughout the remainder of the experiment. The success rate rose more slowly in the totally fresh-oiled situations than in the situations in which only one-half of the sediment surface was contaminated with fresh oil. Animals exposed to sediment with one-half of its surface contaminated with weathered oil showed no reduction in food location and feeding compared to control animals.

Location of food was not necessarily indicative of feeding success. After several observations it was found that while most amphipods contacted the food during the one-hour period, not all of them fed, indicating the animals were not capable of recognizing food. Kittredge, *et al.* (1974) have reported that certain components of crude oil destroyed neuronal dendrites of crustacean chemoreceptor organs. It seems probable that this is also the case with *Boeckosimus affinis*. The recovery of the ability to locate food indicates that this effect is reversible, as amphipods became more successful with time.

Percy (1976) has shown this species rejects oil-tainted food if allowed to choose between contaminated and uncontaminated food. While Percy's studies showed "clean" animals rejected "oiled" food, this study has established that "oiled" animals do not recognize even clean food. Given an oil-contaminated situation, it seems that *Boeckosimus* will not feed if it is contaminated with the oil, and it will not scavenge animals killed or weakened by the oil. As with the survival tests, it appears that the lower boiling point hydrocarbons are largely responsible for this feeding inability, as animals in the weathered-oil situations were much less affected.

Burrowing activity in the sediments treated with fresh oil showed the same suppression for four weeks as was observed in the feeding success trials. Roughly one-half of the animals did not burrow at all during this time. Percy (1977) noted that *Boeckosimus* lost its ability to discriminate against oil-contaminated substrates at high pollutant concentrations. It would seem this ability is also lost with prolonged exposure, even at a lower concentration, as more animals accepted the sediment with time in this study. Percy (1977) also observed that weathering the oil reduced the avoidance response. This study has shown that roughly the same percentage of animals burrowed in the weathered-oil-contaminated sediment, as in fresh-oil situations. However, the weathered-oil sediments produced a large decrease in the burrowing activity with time, with less than 11% of the animals burrowing in the last ten weeks of this study.

Offered a choice of clean or contaminated sediment, animals in the fresh-oil situations preferred the clean substrate by a two to one margin. While the percentages remained the same, the actual numbers burrowing in either oil situation increased with time, as more animals preferred to burrow rather than to lie on the surface. Given a choice of clean or weathered-oil-contaminated sediment, the animals selected

the clean sediment initially, by a nine to one ratio, but they slowly seemed to become less preferential with time, and a one to one ratio was approached.

Since these amphipods are preyed upon by many different animals, the lack of burrowing would seem to subject the individuals to greater risk of being eaten. Such a behavioral trait would seem to court high mortality in a natural situation, but this detrimental behavior would not be evident in a laboratory experiment lacking predators. While it has been established that oil interferes with chemoreceptors, no studies have been done on other types of receptors. Perhaps oil also affects proprioceptors in such a way as to not allow an amphipod to "know" when it is burrowed and no longer exposed to predation.

Contaminated sediment significantly reduced the distance *Boeckosimus* swam with both oil contaminants at both concentrations. A concurrent significant decrease was observed in the amount of time the animals spent moving. The amphipods moved less than did the controls, and when they did move they did so for a shorter distance.

The presence of the fresh oil caused animals to move more slowly with time, however, since less distance was covered in the same amount of time spent moving. Since movement is essential in finding food and potential mates, the presence of oil in the sediments will almost certainly reduce a populations's viability with time, although no serious mortality rate would be ascertained in a standard 96-hour bioassay.

In the *in situ* recolonization study the amphipods showed the same aversion to crude oil exhibited by *Boeckosimus affinis* in the laboratory investigations. All of the species preferred clean to oiled sediment.

Isopods, particularly the large *Saduria entomon*, recolonized all available sediment trays, regardless of the presence of crude oil. Divers reported *S. entomon* crawled into trays as soon as the trays were lowered to the ocean floor, before the trays were set in place. Percy (1977) found both isopod species reported in the recolonization, *S. entomon* and *S. sibirica*, showed little consistent preference for oiled or clean sediment during laboratory testing.

Although isopods were found in oiled-sediment trays throughout the recolonization study, it cannot be concluded that they are immune to oil effects. This study indicated isopods accept oiled sediment throughout a 30-week period. Because these isopods are highly mobile, the chances that any animals remained constantly exposed to oil are very small. More likely, isopods crawled in and out of oiled trays as part of their normal movement. Regardless of the amount of time spent in contact with the oil, the isopods, unlike the amphipods, showed no aversion to the oiled sediment.

Anemones also showed no distinct sediment preference. Foster, *et al.* (1971) reported an *Anthopleura* sp. was resistant to petroleum under field conditions in their work on the Santa Barbara Channel oil spill. The anemone taken in this study, as yet unidentified, is extremely abundant in Elson Lagoon.

George (1971) and Rossi, *et al.* (1976) have noted that some adult polychaetes seem to be resistant to petroleum in sediment. In the present study, the *Nephytes* sp. alone preferred oiled to clean sediment. *Capitella capitata* has been reported as being abundant in sediments

contaminated with petroleum (Rossi , *et al.*, 1976), but was found only after 30 weeks of weathering, and showed a preference for clean sediment at that time. *Pectinaria granulata* and *Scolopolos armiger* exhibited a clear preference for clean sediment throughout the recolonization.

The bivalve mollusks preferred clean sediment. Due to the relative immobility of adults, recolonization potential is probably largely manifested by the larvae. Renzoni (1973, 1975) and Legore (1974) have shown fertilization and larvae are more sensitive to oil than are adults. Whether or not larvae of arctic bivalves will accept an oiled substrate has not been determined.

No conclusions concerning gastropod mollusks can be drawn from this study. Animals were common on the lagoon floor, and were quite mobile. As no gastropods were found on clean or oiled sediment throughout most of the study, it is not possible to conclude what effects, if any, oiled sediment caused. It is likely that recolonization of disturbed areas by gastropod mollusks will be slow.

In summary, the oil contaminated sediment resulted in behavioral changes in benthic invertebrates. Amphipods exposed to oil contaminated sediment had reduced rates of burrowing, feeding and movement. While major mortality did not result when exposed to oil these behavioral changes will surely alter survival rates in the natural ecosystem. Animals with these behavioral changes will be subject to heavy predation pressure.

Even when light hydrocarbons were absent following weathering of the oil, burrowing activity was reduced. The effects of oil in sediment are thus likely to persist beyond the initial lethal stages attributable to light hydrocarbons. This was also shown in the *in situ* recolonization study where differences between recolonization of unoiled and oiled sediment were still apparent 30 weeks after initial contamination. Amphipods clearly avoided recolonization of oiled sediment while isopods showed a neutral response. Alteration in benthic invertebrate populations caused by oil spillages will be transferred through the food web and can be expected to affect populations of higher organisms.

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TABLE 1 Percent of animals surviving exposure to contaminated sediment.

SUBSTRATE TREATMENT	WEEKS OF EXPOSURE 2	4	6	8	10	12	14
100% of sediment treated with fresh oil	100	86	82	80	80	76	76
50% sediment treated with fresh oil	94	84	84	84	82	82	82
100% sediment treated with weathered oil	100	96	96	94	90	90	90
50% sediment treated with weathered oil	94	90	90	90	86	86	84
Control	96	94	94	94	94	90	90

TABLE 2 Percent of animals present feeding after one hour's access to food with exposure to contaminated sediment.

SUBSTRATE TREATMENT	WEEKS OF EXPOSURE 2	4	6	8	10	12	14
100% of sediment treated with fresh oil	24	65	85	93	85	100	97
50% of sediment treated with fresh oil	36	55	100	100	95	95	98
100% of sediment treated with weathered oil	68	60	92	91	89	93	93
50% of sediment treated with weathered oil	94	89	98	96	95	100	95
Control	95	98	100	100	98	92	100

TABLE 3 Percent of animals burrowed in or lying on oil-contaminated and clean sediment

SUBSTRATE TREATMENT	ANIMAL LOCATION	WEEKS OF EXPOSURE 2	4	6	8	10	12	14
100% of sediment treated with fresh oil	burrowed	24	19	51	43	38	53	61
50% of sediment treated with fresh oil	Clean sediment:							
	burrowed	43	33	43	48	51	56	61
	on top	19	24	5	2	5	0	5
	Treated sediment:							
	burrowed	17	29	38	43	24	27	32
	on top	21	14	14	7	20	17	2
100% sediment treated with weathered oil	burrowed	26	27	8	11	2	0	4
50% of sediment treated with weathered oil	Clean sediment:							
	burrowed	85	64	56	40	51	53	45
	on top	2	6	13	18	<1	0	10
	Treated sediment:							
	burrowed	9	18	18	22	28	42	31
	on top	4	12	13	20	19	5	14
Control	burrowed	80	85	87	73	85	92	92

TABLE 4 Means of distances moved (cm) by animals with exposure to contaminated sediment.

SUBSTRATE TREATMENT	WEEKS OF EXPOSURE 2	4	6	8	10	12	14
100% of sediment treated with fresh oil	472	461	626	521	456	391	309
50% of sediment treated with fresh oil	469	526	489	491	414	286	234
100% of sediment treated with weathered oil	544	338	450	424	473	445	403
50% sediment treated wtih weathered oil	442	423	432	332	357	331	303

TABLE 5 Means of percent of total time spent moving by animals with exposure to contaminated sediment.

SUBSTRATE TREATMENT	WEEKS OF EXPOSURE 2	4	6	8	10	12	14
100% of sediment treated with fresh oil	71	71	71	55	32	32	28
50% of sediment treated with fresh oil	45	72	91	73	55	35	43
100% of sediment treated with weathered oil	41	62	81	64	69	76	88
50% of sediment treated with weathered oil	30	56	60	84	52	41	17
Control	64	59	47	89	52	63	75

TABLE 6 Levels of significance of difference of distance moved and total time spent moving of animals exposed to contaminated sediment compared to controls.

SUBSTRATE TREATMENT	DISTANCE MOVED Treatment	DISTANCE MOVED (Time-Oil) Interaction	TOTAL TIME SPENT MOVING Treatment	TOTAL TIME SPENT MOVING (Time-Oil) Interaction
100% of sediment treated with fresh oil	.001	.01	.001	NS
50% of sediment treated with fresh oil	.001	.01	.001	NS
100% of sediment treated with weathered oil	.001	NS	.01	NS
50% of sediment treated with weathered oil	.001	NS	.001	NS

TABLE 7 Spectrofluorometric determination of ranges of amounts of crude oil in *in situ* sediments in μl oil/g sediment.

WEEKS *IN SITU*	OIL CONTENT OF THE THREE SAMPLED TRAYS (μl oil/g sediment) Tray 1	Tray 2	Tray 3	Mean
1	0.0060	0.0083	0.0137	0.0093
2	0.0083	0.146	0.0183	0.0137
3	0.0100	0.0203	0.0114	0.0139
4	0.0123	0.0114	0.0169	0.0135
8	0.0157	0.0214	0.0066	0.0146
30	0.0096	0.0191	0.0120	0.0136

TABLE 8. Numbers of animals recolonizing sediments (per 2500 cm^2) with time.

weeks →	1		2		3		4		8		30	
TAXON AND SPECIES	Control	Oil	Control	Oil	Control	Oil	Control	Oil	Control	Oil	Control	Oil
Amphipoda:												
Pontoporeia femorata	12	0	2	0	4	0	0	1	10	5	28	11
Aceroides latipes	0	0	0	0	0	0	0	0	8	0	24	21
Melita formosa	0	0	0	0	0	0	0	0	14	0	0	0
Gammaracanthus loricatus	0	0	0	0	0	0	0	0	2	0	0	1
Monoculodes sp.	0	0	0	0	0	0	0	0	10	5	0	0
Boeckosimus affinis	0	0	0	0	0	0	0	0	0	0	12	0
Rozinante fragilis	0	0	0	0	0	0	0	0	0	0	4	1
Onisimus sp.	0	0	0	0	0	0	0	0	0	0	0	1
Acanthostepheia behringiensis	12	0	0	0	0	0	0	0	2	0	0	0
Isopoda:												
Saduria entomon	0	0	0	0	0	0	0	0	6	3	0	0
Saduria sabini	2	0	0	0	0	0	0	0	0	0	0	0
Decapoda:												
Pagurus trigonocheirus	0	1	0	0	0	0	0	0	0	0	0	0
Polychaeta:												
Pectinaria (C.) *granulata*	0	0	4	1	2	1	2	0	0	2	4	0
Nephtys sp.	0	0	0	0	0	0	0	3	0	1	0	0
Spio sp.	0	0	0	0	0	0	0	0	0	1	0	0
Brada villosa	8	0	0	1	0	0	0	0	0	0	0	0
Scoloplos armiger	6	0	4	0	0	0	0	0	2	0	0	0
Capitella capitata	0	0	0	0	0	0	0	0	0	0	4	1
Anthozoa:												
Anemone	8	0	14	2	16	3	24	7	0	0	4	8
Bivalvia:												
Astarte borealis	0	1	0	0	2	1	0	0	0	0	4	0
Serripes Groenlandica	0	0	2	1	0	0	0	0	0	0	0	0
Musculus discors	0	0	0	0	0	0	0	0	0	0	0	1
Gastropoda:												
Polinices pallidus	0	0	0	0	0	0	0	0	0	0	4	0
Admete couthouyi laevior	0	0	0	0	0	0	0	0	0	0	4	3
Retusa obtusa	0	0	0	0	0	0	0	0	0	0	0	1

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ABSTRACT

Various biological components of a salt marsh ecosystem were examined for petroleum hydrocarbon accumulation. A site that has been exposed to steady state oil input for 30 years was compared to two control sites from known pristine areas. Three components of crude oil were considered: saturated alkanes, cycloalkanes, and aromatics. Cycloalkanes and aromatics were found to be a better indicator of oil accumulation than the n-alkanes. Benthic organisms, oysters and mussels, demonstrated the greatest enrichment of petroleum hydrocarbons, while the resident, free-swimming Fundulus grandis demonstrated the least petroleum enrichment. A scheme for the fate of spilled petroleum in an estuarine environment is proposed. The major adsorption site was marsh vegetation. Subsequent formation of petroleum-laden detritus appears to be the major transport mechanism of petroleum into the ecosystem. A fluorescence spectrophotometric technique is proposed, whereby the analysis of the total aromatic content of benthic organisms can be used for baseline data and monitoring studies after oil spills.

INTRODUCTION

Oil production and related activities have increased in recent years as the result of increased energy demands. With this increased production, release of oil into the environment can also be expected to increase. Oil production in South Louisiana occurs in both the offshore and estuarine environments. Discharge of oil into the estuaries is of particular concern because (1) of their value as nursery grounds

and habitats for a variety of marine organisms, and (2) there is evidence that certain components of petroleum have detrimental effects on marine life (Hyland and Schneider 1976).

In studying the effects of oil spills, there are accepted chemical parameters for the alkane hydrocarbons that allow the determination of oil accumulation (Scalan and Smith 1970, Gruenfeld and Frank 1977). These parameters are relatively straightforward and work well in close proximity to a spill. But when samples are analyzed at increasing distances from the spill or at some time when degradation of the oil has occurred, alkane parameters are not as definitive. Thus, other aspects of oil accumulation need to be studied.

Much effort has been devoted to the instantaneous or acute effects of an oil spill on specific organisms (Blumer et al. 1970, Burns and Teal 1971, Shaw 1977, Teal 1977). Chronic effects of oil pollution, however, are not as well known (Ehrhardt 1972, Clark and Finley 1973, DiSalvo et al. 1975) and pose a unique problem of which the accumulative effects may impose a significant environmental stress. The Louisiana marshlands provide an excellent opportunity to study the effects of chronic, low-level oil input, as oil production and related activities have existed for over 30 years. Earlier work was primarily concerned with uptake and response to petroleum in regard to a specific organism rather than a systematic study of an ecosystem. Therefore, a need exists to study a variety of organisms that have been exposed to chronic oil input.

In this paper, we attempt to characterize low-level (sublethal) petroleum hydrocarbon uptake and accumulation in various biological components of a South Louisiana salt marsh ecosystem. The objectives are threefold: first, to assess the existing amounts of selected fractions of petroleum in various biological components of this environment; second, to present evidence that benthic organisms are the most sensitive indicators of petroleum exposure; and third, to suggest an analytical methodology for measuring total aromatic hydrocarbon accumulation in tissue exposed to petroleum.

STUDY SITES AND METHODS

Location

Two sub-sites were sampled in each of three sub-environments (Fig. 1). The two control sites were designated Bayou Ferblanc (BF) and Bayou Sevin (BS). BF is a natural salt marsh ecosystem while BS is a brackish environment. The predominant vegetation types are Spartina alterniflora and Spartina patens in BF and BS, respectively. The Leeville oil field (LOF) marsh complex has been previously described by Whelan et al. (1976).

Samples were collected at each of the three sub-environments in late summer of 1976 and early summer of 1977. Organisms that represented a variety of feeding habits were sampled. These include gulf killifish (Fundulus grandis), oysters (Crassostrea virginica), ribbed

mussels (Modiolus demissus), grass shrimp (Palaemonetes sp.), and marsh periwinkles (Littorina irrorata). Marsh grass (S. alterniflora) in each location was also selected. All samples were placed in prewashed, chloroform-rinsed glass containers and stored in ice at 0°C in the field and subsequently frozen until laboratory analysis.

Tissue Extraction

When available, glass-distilled solvents (Nanograde Mallinckrodt) were used. All other solvents were purified by distillation in glass until satisfactory blanks were obtained. Tissue extracts were analyzed using the method described by Warner (1976), except volume reductions were performed with a stream of purified nitrogen gas. When possible, 70 g of sample were homogenized and three 10 g subsamples were analyzed. All data are reported as the average hydrocarbon concentration of the triplicate analyses.

Silica Gel Chromatography

A Kimax glass column (11 mm id x 30 cm long) with a Teflon stopcock and a glass wool plug was filled with a slurry of petroleum ether and activated silica gel (175°C overnight) to a height of 20 cm. A 1 cm layer of activated alumina was then added to the top. Possible trace hydrocarbon contaminants from the silica gel were removed by rinsing the column with 15 ml of methylene chloride followed by 30 ml of petroleum ether. The sample was added to the column in a small volume and the saturated alkane hydrocarbon fraction was eluted with 30 ml of petroleum ether at a flow rate of 2 ml/min. The aromatic fraction was then eluted with 30 ml of 20% v/v methylene chloride in petroleum ether.

Alkanes - Gas Chromatography

The alkane fraction was analyzed with a Perkin-Elmer 900 Gas Chromatograph equipped with dual flame ionization detectors. Alkanes were quantified using external standard techniques and identified by comparison of retention times on two columns of different polarities. A Perkin-Elmer PEP-1 GC Data System was used for peak identification and quantitative analysis. Two columns (2 m x 2 mm id stainless steel) were used for retention time comparisons: 5% FFAP on 80/100 mesh Chromosorb W(AW-DMCS) and 3% OV-17 on 80/100 mesh Chromosorb W HP. The oven temperature was programmed from 100-250°C for FFAP and 150-300°C for OV-17 at 8°/min with 1 minute initial and 12 minute final holds. The detector and injector temperatures were at 325°C with a carrier flow rate of 30 cc/min.

Branched and Cycloalkanes - UCM

Figure 2 illustrates the unresolved complex mixture that was characteristic of the alkane fraction in samples from LOF. A digitizer

was used to measure the total area of the UCM from the C_{15} - C_{28} molecular weight range. The complex composition of the UCM made it difficult to assign absolute concentrations, thus these values represent only relative changes in UCM concentrations between samples.

Aromatics - Fluorescense Spectroscopy

Aromatic fractions were analyzed using fluorescence spectrophotometry. Each fraction was carefully taken to dryness under a stream of purified nitrogen at room temperature, and 20 ml of spectro-quality hexane were added. Samples were analyzed using a Perkin-Elmer 204 Spectrofluorometer equipped with a xenon lamp and coupled with a Perkin-Elmer 165 linear strip chart recorder. Samples were excited at 265 nm and scanned over emission wavelengths from 250 to 450 nm. Spectral intensities at 310 nm and 365 nm, corrected for quenching, were recorded. These wavelengths were chosen because South Louisiana crude oil, which is produced in LOF, exhibits major emission peaks at the 265 nm excitation wavelength. The peak at 310 nm primarily represents naphthalene, alkyl substituted naphthalenes, and other low molecular weight aromatics, while the 365 nm peak represents the higher molecular weight polynuclear aromatic hydrocarbons (PAH). Values for fluorescence intensity reported in this paper are relative units and are useful for comparison of the total aromatic content between samples. No attempt was made to relate these values to absolute concentrations of aromatic hydrocarbons. Figure 3 illustrates two fluorograms of oyster tissue extracts. The control sample contains background levels of aromatic fluorescence whereas the sample from LOF contains pronounced emission intensities at both 310 and 365 nm.

RESULTS

Relative enrichment factors in three classes of petroleum hydrocarbons, namely, saturated alkanes, UCM alkanes, and aromatics in tissue extracts from resident organisms in Leeville Oil Field, are presented in Tables 1-3. Table 1 summarizes the alkane data for the two sampling periods. The last column in each set contains a value derived by dividing the alkane hydrocarbon concentration of a particular oil field organism by the average concentrations in both control organisms. This term is defined as the enrichment factor. For example, oysters in LOF from 9/76 contain 1.3 times the alkane content as the natural or background levels found in the tissue of the control oysters. In the first set of samples all organisms showed some enrichment in alkanes. The highest enrichment factor was obtained from the marsh grass (18.12) and the lowest for the oysters (1.29). Fundulus grandis had an average enrichment of 1.4 with no difference between males and females. In the second set (7/77) there was no alkane enrichment in the oysters, mussels, or grass shrimp. No samples were taken of the grass or periwinkles. Enrichment was present in the average value for all fish, but the data was more variable than in the first run. Enrichment ranged from a high of 2.14 for 41-60 mm females to a "negative" enrichment of 0.65 for 61-80 mm females.

Table 2 lists the enrichment factors for the unresolved complex mixture (UCM). This quantity represents relative enrichment of the more soluble cycloalkanes. All organisms exhibited enrichment in this parameter in both the first and second analyses. In all cases, except the mussels and 61-80 mm male fish, the enrichment factor was greatest for the 9/76 set of samples. There seemed to be no pattern in the difference between length class and sex for F. grandis. The large enrichment in cycloalkanes for all organisms compared to the normal alkanes may result from the greater solubility of compounds that comprise the UCM. The large enrichment factor for the grass is primarily caused by physical adsorption of oil on the plant roots, stems, and leaves as opposed to biochemical uptake at the cellular level.

Table 3 lists enrichment factors for the total aromatic hydrocarbons at fluorescence emission peaks of 310 nm and 365 nm. Marsh grass and periwinkles, as expected, demonstrated the greatest enrichment of all organisms in the 9/76 analyses. Overall, F. grandis showed only slight enrichment in this fraction. This result may be explained by solubility differences between each of the three petroleum fractions under consideration. Aromatic hydrocarbons are significantly more water soluble than saturated alkanes but probably not as soluble as the compounds responsible for the UCM. These data suggest that the free swimming, carnivorous F. grandis probably accumulate petroleum hydrocarbons in direct relation to their solubility characteristics. Grass shrimp in the 9/76 samples showed no enrichment. This resulted from abnormally high fluorescence, especially at 365 nm, for grass shrimp from BS. No explanation is available at this time, but this anomaly was present in all three replicates. The 7/77 samples had considerably higher enrichment factors than 9/76 samples for all of the organisms examined. The killifish exhibited increases in enrichment of two to three times, which was not reflected in the average because of low enrichment for 61-80 mm females. This was the result of high peak intensities for the samples from control BS. Again, no explanation is available for this anomaly.

DISCUSSION

In the Leeville oil field, which is only one of the many producing fields in the South Louisiana wetlands, petroleum is introduced into the environment in several ways. Approximately 6 x 10^6 barrels of brine water, which contain saturation concentrations of petroleum, are annually discharged into this environment (Texaco Oil Co., personal communication). Small but relatively periodic spills occur from pipeline leaks, overflow of asphalt holding tanks, well maintenance, and drilling operations. These inputs are variable and difficult to quantify but probably constitute a significant source of petroleum. As oil production and recovery operations have been active in Leeville for 30 years, certain components of the original ecosystem have been modified. For example, the population of hydrocarbon-consuming bacteria in Leeville sediments has increased several fold compared to uncontaminated salt marsh sediments (Hood et al. 1975). The population structure and distributional patterns of gulf killifish (F. grandis) have not been significantly altered between oil field and control sites. However, killifish captured in LOF

produced fewer ova than the controls, which suggests a fecundity change has occurred (May 1977).

Figure 4 proposes a mechanism for the fate of discharged oil in a salt marsh ecosystem. Once oil is released into the environment, the surface slick is either partially adsorbed by particulate matter, exposed sediments and in the stems and roots of marsh vegetation, or partially solubilized in the water column. Marsh vegetation seems to be the major adsorption site of discharged oil. Large amounts of alkanes, cycloalkanes, and aromatics are adsorbed by the grass. When the grass dies, the detritus either becomes incorporated into the sediment or food for marsh organisms. Sediments are probably the most significant long-term storage sites of petroleum hydrocarbons, and act as a sink for oil, expecially in estuarine environments (Blumer and Sass 1972, Farrington and Quinn 1973, Youngblood and Blumer 1975, Meyers 1976). Sediments adsorb dissolved hydrocarbons and accumulate oil-coated particulate matter during depositional processes. In addition, benthic microbial communities break down the alkanes, while cycloalkanes and aromatics are considerably more resistant to oxidative metabolism (Vandermeulen et al. 1977). Sediments then become enriched in cycloalkanes and aromatics relative to the more labile alkanes. These compounds can then be released back into the water column at some future time through sediment reworking processes such as storm waves, bioturbation, and dredging activity (Blumer et al. 1970; Vandermuelen et al. 1977).

In this study aromatic and cycloalkane enrichment seemed to be a more consistent indicator of low-level, chronic petroleum exposure than alkane enrichment. In the benthic organisms, oysters and mussels, enrichment in aromatics and cycloalkanes in both sample runs indicated oil accumulation, while alkane enrichment was not as definitive. The reasons for this may be found in the nature of these hydrocarbons and the biology of benthic organisms. The sessile benthic habitat and filter-feeding characteristics of benthic organisms predispose them to petroleum accumulation. Also, previous studies have shown that benthic organisms are excellent indicators of their environment (DiSalvo et al. 1975, Burns and Smith 1977). As filter-feeders, oysters and mussels are exposed to both adsorbed and soluble hydrocarbons. Cycloalkanes (UCM) and low molecular weight aromatics are the most soluble fraction of crude oil, while the PAH, the polar nature of which increases their adsorptive capacity, are selectively adsorbed to suspended particulate matter (Lee 1977a). Alkanes, however, are the least soluble fraction of crude oil and are only partically adsorbed to suspended matter. Therefore, benthic organisms would be exposed primarily to aromatic and cycloalkane fractions of crude oil in the water column. Their benthic habitat exposes them to additional contamination by these compounds, which are released by the sediments. Metabolism of hydrocarbons by benthic organisms has not been conclusively proven (Lee, Sauerheber, and Benson 1972, Stegeman and Teal 1973, Fossato and Canzonier 1976). Depuration of unmetabolized hydrocarbons can occur after exposure when benthic organisms are in a clean environment. The quantity of hydrocarbons released depends on exposure time, concentration, and the lipid content of the animal (Boehm and Quinn 1977). After short-term exposure, depuration can be complete, but chronic exposure (years) allows hydrocarbons to be retained in the organism's natural lipid pools

(Blumer et al. 1970, Stegeman and Teal 1973, DiSalvo et al. 1975, Bohem and Quinn 1977). Alkanes have been shown to be the most susceptible to depuration, while the aromatics and cycloalkanes are retained for longer periods of time (Blumer et al. 1970, Ehrhardt 1972, Lee, Sauerheber, and Benson 1972, Stegeman and Teal 1973, Neff et al. 1976). Considering the types of hydrocarbons that can be taken up by benthic organisms and their respective depuration rates, aromatic and cycloalkane hydrocarbons seem to be the most persistent following chronic petroleum exposure.

Organisms that reside in the water column, grass shrimp and gulf killifish, exhibited enrichment in cycloalkanes and aromatics but not in the alkanes. As in the benthics, total alkane concentration was not a good indicator of oil accumulation. Aromatic and cycloalkane enrichment, however, did indicate oil accumulation by these organisms. The lack of alkane enrichment by the killifish may be the result of lower exposure because (1) alkanes are relatively insoluble and therefore uptake through the gills is minimal, (2) alkanes absorbed to detritus would not be taken up by killifish because detritus is not part of its diet (Day et al. 1973), and (3) F. grandis has also demonstrated the ability to discriminate against petroleum-derived alkane hydrocarbons in its food (Teal 1977). Alkanes that are ingested by killifish are subject to enzymatic breakdown by the liver, which further reduces accumulation of these compounds (Lee, Sauerheber, and Dobbs 1972, Lee 1977b). The accumulation of cycloalkanes and aromatics by killifish is the result of (1) their water solubility, which allows uptake through the gills and (2) their slower rate of metabolism than the alkanes. As with the benthics, exposure time would determine if these compounds are stored in the more stable lipid pools, where depuration of cycloalkanes and aromatics would be slower. Grass shrimp exhibited degrees of petroleum hydrocarbon enrichment between the killifish and benthics. This is the result of its water column habitat, and its detritus-rich diet, which would expose them to both soluble and adsorbed hydrocarbons as the benthics, but not the additional contamination from the sediments. Metabolism of petroleum hydrocarbons by grass shrimp has not been directly shown but may be inferred from investigations with other crustaceans (Lee et al. 1976, Neff et al. 1976). Even if metabolism doesn't take place, release of these compounds in an unaltered state is possible in a clean environment. This process has been shown to occur at a much faster rate in grass shrimp than in molluscs (Tatem 1977).

These results indicate that in studying low-level, chronic oil input in a salt marsh estuary (1) benthic organisms seem to be the most sensitive and definitive environmental indicators of oil pollution, and (2) cycloalkanes and aromatics are the components of crude oil that should be examined. The alkanes were not a consistent indicator of oil accumulation because they are (1) relatively insoluble, (2) easily metabolized by organisms, (3) subject to microbial degradation, and (4) manufactured by living systems; whereas the cycloalkanes and aromatics are (1) more soluble, (2) resistant to metabolism by organisms, and (3) unique to petroleum. The aromatics would be the easiest to study because of the speed and sensitivity of the fluorescence technique. Fluorescence could be used as a fast scan to screen tissue samples for aromatic content. Selected samples from this group could be further analyzed in

detail by gas chromatography/mass spectrometry (GC/MS) for identification of the molecular distribution of aromatic hydrocarbons.

Monitoring the extent and recovery of an estuarine environment following an oil spill will ultimately involve establishing low-level petroleum concentrations within and surrounding the affected area. Results from this study indicate that low-level petroleum enrichment within a salt marsh estuary is best determined by analysis of aromatic and UCM hydrocarbons from tissue in benthic organisms, namely, oysters and mussels. Saturated alkane hydrocarbons were not a definitive indicator because of their lower solubility and relative loss through metabolism and microbial degradation. In addition, naturally occurring alkanes dilute those derived from petroleum. Cycloalkanes and aromatics, conversely, are unique to petroleum.

Use of fluorescence spectroscopy to determine the total quantity of aromatic hydrocarbons in tissue samples provides a rapid and sensitive technique for analyzing low-level concentrations of petroleum hydrocarbons. This methodology could be used as a screening procedure to establish samples or areas that contain "cutoff" levels of petroleum contamination. Selected samples from this group could be subjected to a more time-consuming, detailed analysis by gas chromatography/mass spectrometry for identification of the molecular distribution of aromatic hydrocarbons.

CONCLUSIONS

1) Low-level petroleum contamination in a salt marsh estuary was the most definitive in the enrichment of UCM and aromatic hydrocarbons from tissue in macro benthic organisms.

2) Adsorption of oil on marsh vegetation and subsequent formation of petroleum-laden detritus appears to be the major transport and dispersal mechanism of petroleum into the environment.

3) The speed and sensitivity of fluorescence analysis of tissue extracts provide a rapid and sensitive technique for determining the total aromatic hydrocarbon content. Samples containing aromatic content above a certain value can be selected for detailed GC/MS analyses.

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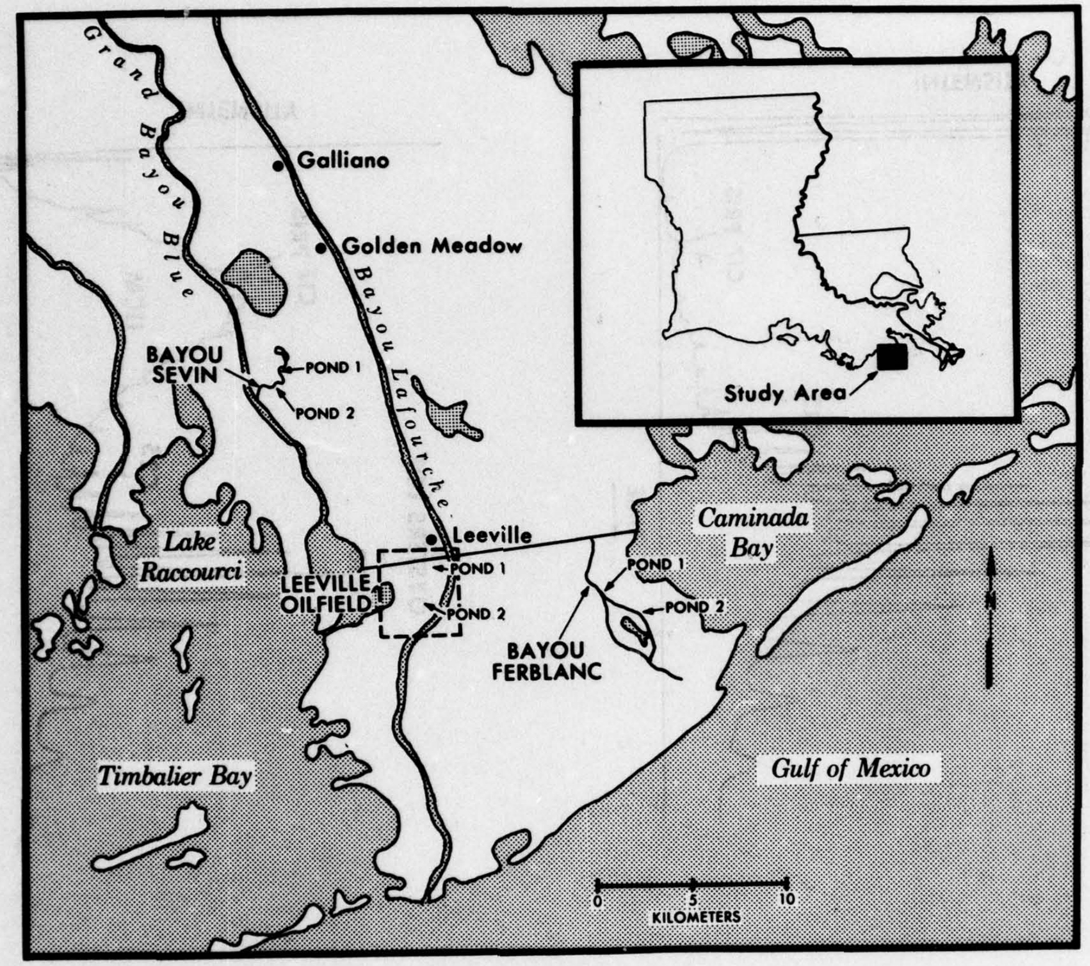

Fig. 1. Map of Study Area in South Louisiana

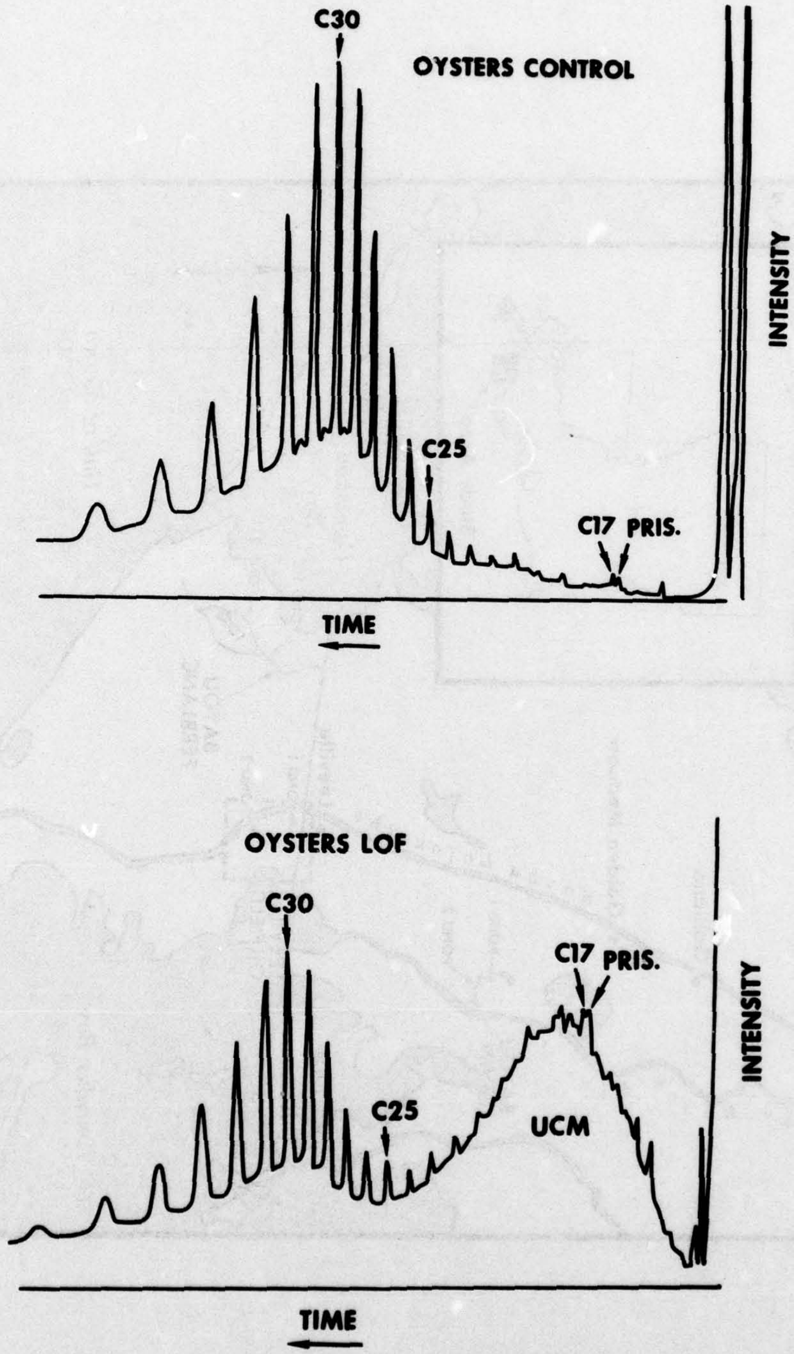

Fig. 2. Chromatograms Showing Unresolved Complex Mixture (UCM).

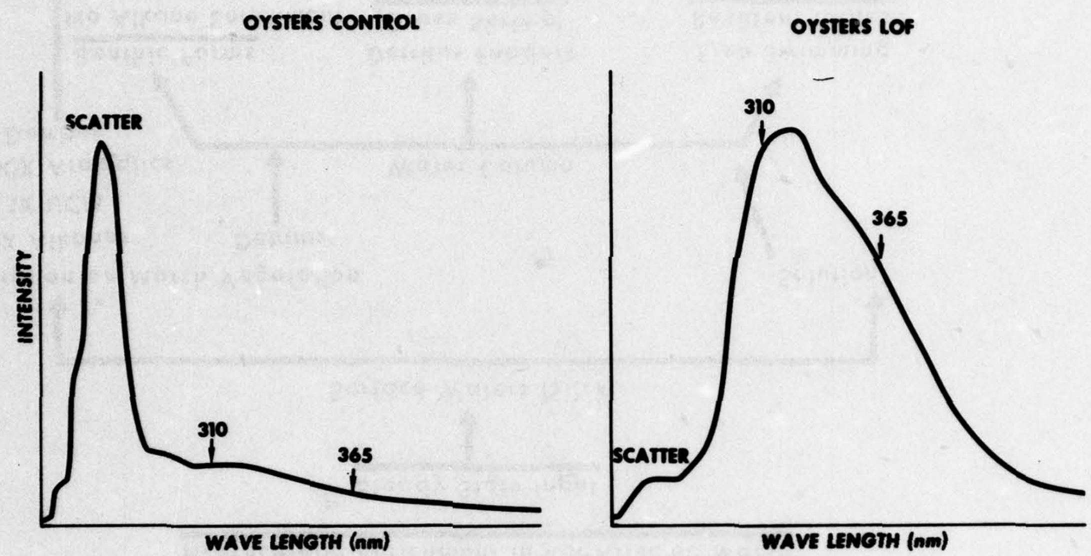

Fig. 3. Fluorogram Showing Differences in the Intensity of Peaks.

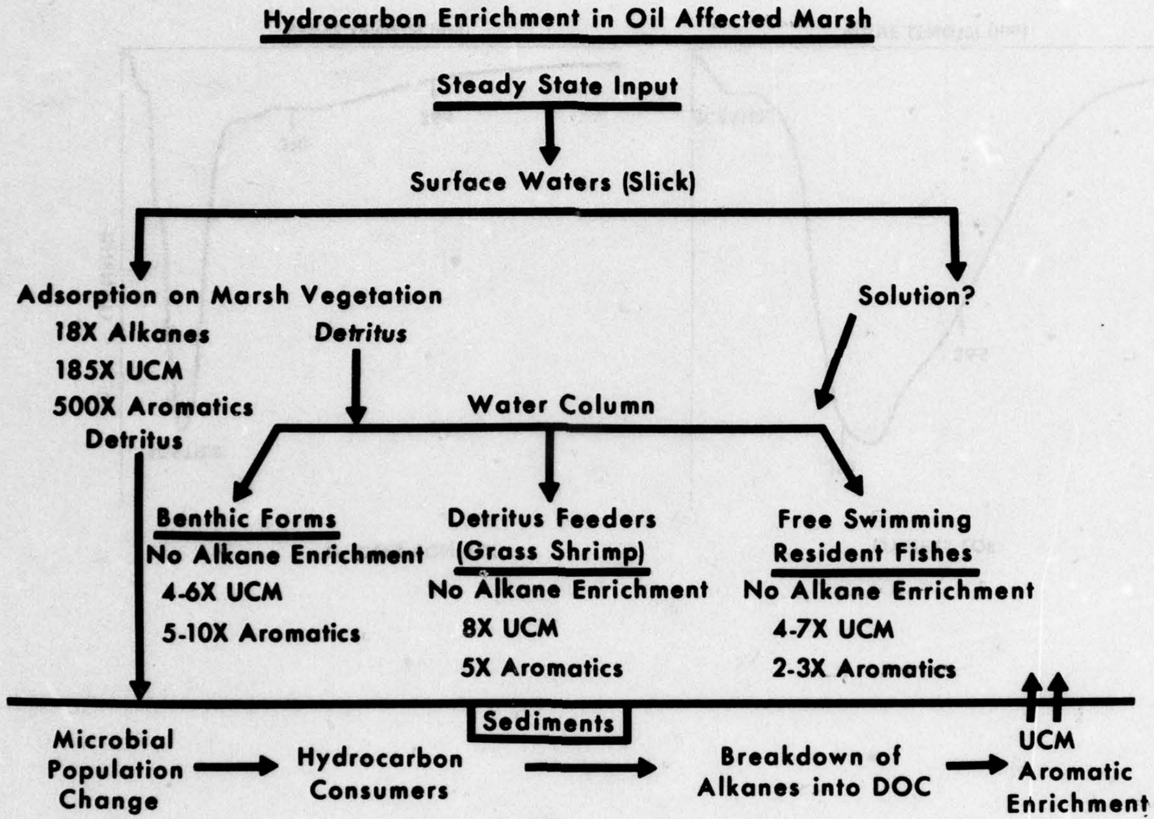

Fig. 4. Schematic Representation of the Fate of Oil in a Salt Marsh Ecosystem.

Table 1

Total Identifiable Alkane Hydrocarbons
$C_{15} - C_{28}$ in ppm

	9/76				7/77			
Organism	NC	LOF	SC	E.F.	NC	LOF	SC	E.F.
Oysters	0.560	0.885	0.809	1.29	0.149	0.396	0.647	0.99
Mussels	0.238	0.376	0.171	1.84	0.903	0.360	0.781	0.43
Grass Shrimp	0.183	0.345	0.121	2.27	0.112	0.180	0.354	0.77
Grass	0.791	17.256	1.114	18.12	—	—	—	—
Periwinkles	—	1.613	0.688	2.34	—	—	—	—
Fish*								
41-60 M	0.365	0.414	0.230	1.35	0.736	0.694	0.543	1.09
41-60 F	1.453	1.163	0.307	1.32	1.019	1.670	0.539	2.14
61-80 M	0.326	0.416	0.253	1.44	0.203	0.431	0.431	1.36
61-80 F	0.325	0.408	0.271	1.37	0.542	0.299	0.382	0.65
>80 M	—	—	—	—	0.285	0.529	—	1.86
>80 F	—	—	—	—	0.378	0.240	0.256	0.76
Males (Avg)	0.346	0.415	0.241	1.41	0.408	0.551	0.487	1.23
Females (Avg)	0.889	0.785	0.289	1.33	0.646	0.736	0.392	1.42
All Fish (Avg)	0.617	0.600	0.265	1.36	0.527	0.643	0.439	1.33

*numbers designate length class (mm) and leters M or F designate sex male or female

$$\text{E.F.} = \text{Enrichment Factor} = \frac{\text{LOF}}{\frac{(\text{NC} + \text{SC})}{2}}$$

NC = North Control = Bayou Sevin

SC = South Control = Bayou Ferblanc

Table 2

Enrichment Factors (E.F.) for the Unresolved Complex Mixture (UCM)

Organism	9/76	7/77
Oysters	10.67	3.25
Mussels	3.48	6.03
Grass Shrimp	12.50	5.06
Grass	184.49	—
Periwinkles	6.63	—
Fish		
41-60 M	6.01	3.98
41-60 F	11.29	5.00
61-80 M	7.27	9.04
61-80 F	2.97	1.92
>80 M	—	7.22
>80 F	—	3.29
Males (Avg)	6.25	5.32
Females (Avg)	8.08	3.54
All Fish (Avg)	7.07	4.04

Table 3

Enrichment Factors (E.F.) for the Aromatic Fraction at Fluorescence Peaks of 310 nm and 365 nm

Organism	9/76 310	9/76 365	7/77 310	7/77 365
Oysters	4.85	5.28	13.27	20.33
Mussels	9.11	5.71	6.30	9.85
Grass Shrimp	0.91	0.15	4.35	9.71
Grass	326.27	774.69	—	—
Periwinkles	12.11	14.67	—	—
Fish				
41-60 M	1.27	1.36	2.30	2.48
41-60 F	1.16	1.39	3.45	4.83
61-80 M	1.23	1.53	3.20	4.90
61-80 F	2.68	8.80	0.69	1.29
>80 M	—	—	2.48	3.44
>80 F	—	—	3.03	4.28
Males (Avg)	1.24	1.47	2.66	3.14
Females (Avg)	1.91	5.25	1.81	2.60
All Fish (Avg)	1.54	2.94	1.89	2.86

ECOLOGICAL CONSEQUENCES OF PETROLEUM SPILLAGE IN PUERTO RICO

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ECOLOGICAL CONSEQUENCES OF PETROLEUM SPILLAGE IN PUERTO RICO

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In order to develop an approach that can aid in assessing the impacts of oil spills a typical Puerto Rican coastal environment is viewed in terms of its major marine ecosystem: coral reefs, seagrass beds and mangrove forests. Case studies of oil spills in Puerto Rico have involved comparison of abundance and diversity of organisms and species in spill areas versus carefully-matched, similar environs in no-spill areas. The relative vulnerability of these ecosystems has been demonstrated. Coral reefs are least impacted owing to their sub-tidal nature and high energy situation. Beds of the seagrass *Thalassia testudinum* exhibit relatively minor, short-term effects. This comparative approach has shown, however, that oil coating of fringing stands of the red mangrove *Rhizophora mangle* and the associated intertidal communities of their prop roots impairs productivity and destroys the attached organisms. Oil becomes trapped and may not be retrieved or cleaned from the mangrove forest. Analysis by GC/IR of extracts from sediments within the mangal have shown the abundance and persistence of petroleum hydrocarbons in correlation with the absence of benthic organisms four years after an oil spill.

INTRODUCTION

Increased shipping and utilization of crude and other oils in Puerto Rico and in the rest of the tropical world increases the prospects of petroleum contamination in the tropical marine environment. In Puerto Rico, several oil spills of varying mangnitude have already occurred. Case studies of oil spills in Puerto Rico demonstrate the relative vulnerability of the tropical environment. Accumulation of petroleum in and around mangrove swamps can be substantial and persistent. Seagrasses and coral reef communities can also be affected. In assessing the ecological significance of oil spillage in these waters it is convenient to study the acute effects as well as the biological availability and long-term chronic effects on organisms of the affected areas.

In order to develop an approach that ca. aid in assessing the impact of oil spills and long-term petroleum hydrocarbons contamination, a typical Puerto Rican coastal environment is viewed in terms of its major marine ecosystems: coral reefs, seagrass beds and mangrove roots. Mathews (1967) has described the littoral flora and fauna of Puerto Rico and offers the typical zonation for each component ecosystem. Her review is extensively drawn upon in the foregoing discussion. By analyzing each of the major component ecosystems and the oil spill experience of Puerto Rico it is possible to reach some preliminary conclusions as to actual and potential consequences of petroleum spillage in Puerto Rico.

PUERTO RICO'S COASTAL ENVIRONMENT

Coral Reef Ecosystems

The reef formation is divided into two major parts: the seafront or outer reef and the back or leeward reef which may deepen into a lagoon and may form a reef island. Such corals as *Acropora palmata*, *Montastrea annularis*, *Porites asteroides* and *Diploria labyrinthiformis* live on the outer reef where waves break. Green calcareous algae such as *Udotea* and *Halimeda* species along with phytoplankton are the basic producers of the community. The main consumers are the corals and also found are urchins of the genera *Diadema* and *Echinometra*. Polychaeta, brittle stars, and the spiny lobster may also be found here. Behind the reef front, protected water forming a small lagoon, allows for delicate types of coral to develop. Another food chain exists there which includes non-calcareous and calcareous algae as primary producers and corals such as *Porites porites*, *Acropora cervicornis*, and *Zoanthus pulchellus* as the primary consumers. Many soft corals occur in this area of the reef. Under the corals occur detritus feeders like brittle stars and plankton feeders like several genera of sponges including *Haliclona*, *Adocia* and *Callyspongia*. Also, the sea urchins *Diadema* and *Echinometra* and the fanworm *Sabellestarte magnifica* are very abundant here. Many small, scavenging crabs and sea cucumbers occur. Octopi and moray eels often use the coral rubble as their habitat. The coral rubble affords shelter for a wide variety of animals.

Johannes (1975) found no conclusive evidence that oil floating above reef corals damages them. After 25 days of observation, and after floating various types of oil over groups of different corals, no visible evidence of damage was noted. Rutzler and Sterrer (1970) reported that corals escaped readily observable damage during a Panama oil spill where inshore littoral fauna was widely affected. This was presumably due to the fact that the corals were continually submerged. Spooner (1970) observed no damage to reef communities in Tarut Bay, Saudi Arabia, in an area of long-term chronic oil pollution. Deleterious effects have been seen on corals exposed to diesel and Bunker C fuels under experimental conditions. These effects ranged from decrease in growth rate to death after a few days (Birkeland, et al., 1973).

Reef-associated fishes and invertebrates can be killed by oil spills. In Puerto Rico, Diaz-Piferrer (1962) observed extensive mortality of marine fauna and flora in the sublittoral and intertidal zones in Guanica Bay resulting from a large spill of crude oil.

Seagrass Ecosystem

Tropical seagrass beds are frequently found in the vicinity of coral reefs with important interactions between them. In the Caribbean the genera *Halodule*, *Syringodium*, *Thalassia* and *Halophila* occur. Seagrasses contribute significantly to the maintenance of the coastal ecosystem of the tropics and near tropics in numerous ways (Zieman,1975).

Since the decimation of the green sea turtle by overfishing there has been little direct grazing pressure on these beds. In *Thalassia* beds, 90% or more of the energy becomes available to higher trophic levels via a detritus food web. Seagrasses have a high productivity and the leaves support large microbial and epiphitic populations. The leaves reduce current velocity near the sediment surface and promote sedimentation of organic and inorganic particles. The extensive roots and rhizomes bind and stabilize sediments hindering erosion.

Thalassia testudinum is the most common marine grass found around Puerto Rico at depths from one to 20 m. *Thalassia* is a transition stage between coral reefs and the mangroves. It roots in shallow, well-exposed areas of coral decay that has been caused by the accumulation of sediments. Most of the animals found here do not depend on *Thalassia* per se. These animals find shelter in the grass, but are primarily algal or filter-feeders or derive nutrients from bottom sediments. Algae of the genera *Penicillus, Halimeda, Udotea, Dictyota* and *Caulerpa* are abundant here. Some corals such as *Manicina areolata* also flourish here. Bottom feeding sea cucumbers, *Ludwigothuria mexicana*, the filter-feeder pen shell clam, *Pinna carnea* and the sea star, *Oreaster reticulatus*, are abundant members of the community. Algal feeders in the system are *Tripneustes esculentus* and *Lytechinus variegatus*. The juveniles of the queen conch *Strombus gigas* and the fighting conch *Strombus pugilis* are found here. These are nocturnal carnivores feeding on abundant small gastropods. Many fishes of the coral reefs forage on species living in the grass beds. Populations of reef fishes are larger where the reefs are adjacent to seagrass beds (Zieman, 1975).

Seagrasses are generally subtidal and are thus less susceptible to damage from oil than other organisms, especially those in the intertidal zone. During the Santa Barbara oil spill in 1969 severe damage occurred to *Phyllospadix torreyi* growing in the intertidal zone (Foster, et al., 1971). Plants of the subtidal and extreme low intertidal zones were relatively protected from oil contact and were largely undamaged.

In Puerto Rico, destruction of seagrass beds have been observed from large oil spills. Diaz-Piferrer (1962) found that beds of *Thalassia testudinum* were severely affected by oil spilled on the south coast of Puerto Rico. The turtle grass was deteriorated over a period of several months, and the normal algal flora was denuded and replaced with blue-green algae. Interaction of sediment and oil can result in agglomeration into large lumps which increase the buoyancy of the sediments making their removal by currents easier. Seagrasses tend to stabilize the fine-grained sediment, but the seepage of oil into the grass beds promotes the loss of sediment. Diaz-Piferrer (1962) reported the loss of 3000 m^3 of sand from Tamarindo Beach in Guanica, Puerto Rico in less than one week due to this effect.

Mangrove Ecosystem

Mangroves are trees from a wide variety of families and are important plant ecosystems that fringe the world's tropical and subtropical seashores. A reported 75% of the coastlines between 25°N and 25°S are dominated by mangroves (McGill, 1959). In Puerto Rico, three species occur: *Avicennia germinans* (black), *Laguncularia racemosa* (white) and *Rhizophora mangle* (red). The latter is the most abundant and occurs closest to the sea with its extensive prop root system submerged in the water. A large attached community of plant and animal life finds a habitat on these roots. *Rhizophora* is viviparous producing an abundance of flowers and later seeds which germinate while still on the trees to form propagules. These propagules are viable seedlings that drop and drift away until they sink and colonize a new area should they find the proper substrate. *Rhizophora* may form colonies well offshore and on reef islands. The substrate is usually covered by water even at low tide. The red mangrove will collect soil and raise the land level. Mangroves play a pioneer role by colonizing muddy estuarine shores and thus initiating a landward succession leading to the establishment of a tropical forest. The trees can be divided into three main zones: the branches of the trees, the terrestrial roots and the submerged roots.

Several birds have their habitat in the branches of the trees, for example the Golden Warbler *Dendroica petechia*, and the Mangrove Clapper Rail *Rallus longirostris*. The terrestrial roots are dominated by mobile animals such as crabs and mollusks. The snail *Littorina angulifera* abounds near the water line. Scavenger grapsid crabs like *Aratus pisonii* and *Grapsus grapsus* are found here. Near the muddy bottom another crab, *Uca pugnax* is abundant and also the large edible crab, *Cardisoma guanhumi*, can be found here. The submerged roots can harbor in excess of 100 species of plants and animals. Odum and Heald (1972) have demonstrated the importance of mangroves and the flux of their photosynthetic energy through a complicated food web based on mangrove detritus which helps sustain tropical estuarine ecosystems. A simplified mangrove detrital food web is outlined in Figure 1 (Teas, 1974). For the *Rhizophora mangle* forest of Guayanilla Bay, south coast of Puerto Rico, the major species of the root community are outlined in Table 1 (López and Teas, 1978). Hazardous chemical contaminants (as can be found in petroleum) that enter the mangrove ecosystem could become available to many organisms as well as to the human consumer through numerous paths in the food web.

Odum and Johannes (1975) reviewed the effects of petroleum pollution on mangroves and concluded that there is little doubt that petroleum and petroleum by-products can be harmful to mangroves. Damage by an oil spill on the Atlantic Coast of Panama was more serious to mangroves than to coral, sandy beach, or rocky shore communities (Rutzler and Sterrer, 1970). In this event, seedlings of *Rhizophora* were killed along with turtles, birds, intertidal invertebrates and algal mats of the mangrove community. An oil spill in Tarut Bay, Saudi Arabia, defoliated mangroves, but many plants survived (Spooner, 1970). Generally, oils high in aromatics are more phytotoxic. Light

oils are toxic to plants, but in the tropics they evaporate rapidly. Heavy oils lose their volatile fraction rapidly and are toxic to mangroves principally because the thick residues cover lenticels in prop roots, pneumatophores and trunks. The aeration systems is kept from functioning and the trees are killed by making the roots anaerobic.

Teas (1978, Personal Communication) has observed *Rhizophora* trees in Puerto Rico surviving well in spite of one-half to one-third of their prop roots being covered with thick oil while their good roots were in soil that was also oil laden. In Puerto Rico extensive damage to mangroves from oil spills have been reported by Diaz-Piferrer (1962) for mangroves of Guanica Bay and by Gilmore (1970) for mangroves of Guayanilla Bay.

PETROLEUM SPILLAGE IN PUERTO RICO

The *Argea Prima*

On July 16, 1962 the Italian tanker *Argea Prima*, aground on a reef off Guayanilla Bay, dumped 10,000 tons of crude oil into the sea in order to refloat. The oil was blown ashore and transported westwardly by currents for about 20 miles affecting the shoreline and offshore reefs of the southwest coast of Puerto Rico. Diaz-Piferrer (1962) studied the impact of this spill. He estimated that 3000 m^3 of sand were eroded from a beach in Guanica due to increase buoyancy of the beach material when mixed with the oil. The oil striking the mangrove swamps settled among the roots virtually destroying that habitat in heavily affected areas. Large mortalities were observed in populations of adult and juvenile lobsters, crabs, sea urchins, star fishes, sea cucumbers, gastropods and a variety of fishes. Also affected were sub-littoral and intertidal plants. Seagrass beds of *Thalassia* were greatly affected and large rocky areas were completely denuded of algae.

The *Ocean Eagle*

On March 3, 1968, the oil tanker *Ocean Eagle* ran aground and broke in two at the entrance of San Juan Harbor spilling its cargo of crude oil. The spill affected the harbor and tourist beaches east and west of San Juan. Cerâme-Vivas (1968)reported damage to pelicans, numerous invertebrate animals on the beaches, and observed lesions on 95% of the fish population of *Ophistonema oglinum*. It was not clear if the lesions were directly caused by the oil or the materials used to control it. Bioassays using some of the emulsifiers used for clean-up demonstrated the toxicity of these materials. It was observed that dispersants created more damage to tropical marine organisms than they prevented by dispersing the oil through the water column.

The *Zoe Colocotronis*

On March 18, 1973, the Greek tanker Zoe Colocotronis ran aground near the southwest shore of Puerto Rico. Venezuelan crude oil (37,000 barrels) was released in order to refloat the vessel. About 24,000

barrels of crude oil drifted and came ashore in Bahía Sucia, in the municipality of Cabo Rojo. The oil washed into, and became trapped in, the mangroves killing many invertebrate animals (TRC, 1973). About 1.0 hectare of red and black mangrove trees were defoliated and died during the three years following the spill (Nadeau and Berquist, 1977). *Thalassia* beds were also affected, defoliation of the grass being observed. A reevaluation of the spill area by UPR (1977,a,b) demonstrated that after nearly four and one-half years the mangrove root communities show reduced number of species and population as compared to similar reference areas. Also plant biomass and number of species in *Thalassia* beds were reduced as compared to reference areas. Chemical analysis showed the persistence of the oil 4 1/2 years later.

Other Spills

On December 9, 1975 a barge carrying 10,000 barrels of Bunker C and 2,000 barrels of diesel fuel spilled its cargo after running aground just west of Isla de Cabras on the north coast of Puerto Rico. The oil stranded on the face of the beach along Ensenada de Boca Vieja, a large embayment west of San Juan Harbor. Cintrón (1975) observed the formation of patches of quicksand in this area due to the oil, even though it was not chemically treated. Quicksand formation from oil spills elsewhere had been attributed to chemicals used to dispersed the oil.

In March, 1977 an estimated 1,000 barrels of Venezuelan crude oil were spilled during offloading in Guayanilla Bay. Extensive stands of red mangroves were coated with oil causing damage to the mangrove root communities on the western portion of the bay. Evidence of oil still remains on those roots more than a year after the spill, although the trees appear to be surviving. Accidental oil spills occur occasionally in Guayanilla Bay, the site of a large petrochemical complex.

Petroleum Hydrocarbons in Guayanilla Bay

Guayanilla Bay and adjacent Tallaboa Bay, on the south coast of Puerto Rico, have received chronic discharges of refinery and petrochemical wastes for about 25 years (Figures 2 and 3). As a result, extensive areas of Tallaboa Bay are depleted of all life and petroleum hydrocarbon residues are widely distributed throughout the area sediments (Figure 3). Reports of foul smell and taste of commercially important fishes are attributed to petroleum contamination. An extensive research program on the impact of energy-related contamination in this area is being conducted at the University of Puerto Rico's Center for Energy and Environment Research. As part of this effort, it has been observed that other dangerous contaminants, including mercury, generally follow the same distribution pattern as the oil suggesting possible chemical association among these contaminants. Biological degradation is evident in these areas of heavy contamination.

To further assess ecological impact we propose to investigate the biological availability of dangerous hydrocarbons in the mangrove-associated community given their importance and the link to man in the

food chain. In this approach, key organisms in the food chain are analyzed by GC/MS. Should dangerous chemicals be found, this would be evidence of bioavailability and the source and mechanism of transfer would then be studied through microcosm experiments in the laboratory.

CONCLUSION

Ecological consequences of petroleum spillage in Puerto Rico can be severe to the various kinds of ecosystem component corals, seagrasses and mangroves. The most severe and longest lasting impact is likely to be that on the mangrove communities. Here the initial acute effect can be large, but also chronic, long-term effects are possible. Given the important role of the mangrove detrital food chain in the sustenance of the coastal marine ecosystems in Puerto Rico, and the link to man, the question of biological availability and subsequent accumulation and transfer in the food web of hazardous petroleum-related compounds should be thoroughly researched. Such efforts are underway at the Center for Energy and Environment Research. Based on past oil spill experience in Puerto Rico and information considered in this paper on effects of oil spills on tropical, marine communities contingency plans can be developed to respond in the event of an oil spill. Although all components of the ecosystem are equally valuable and important, it appears that special efforts should be made to protect mangrove areas from oil as the impact here has for reaching implications.

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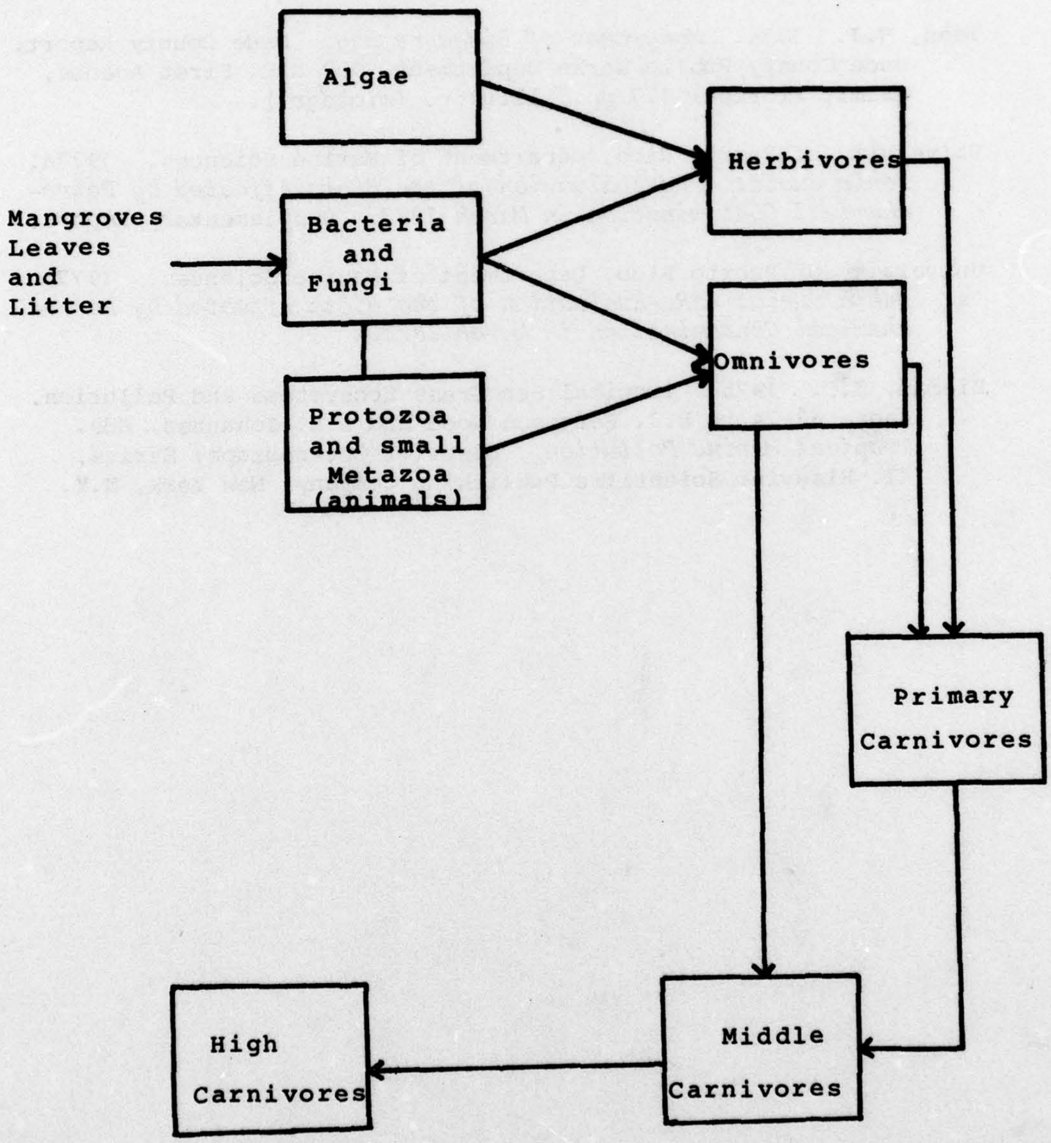

Figure 1. Simplified Mangrove Detritus Food Chain.
(From Teas, 1974)

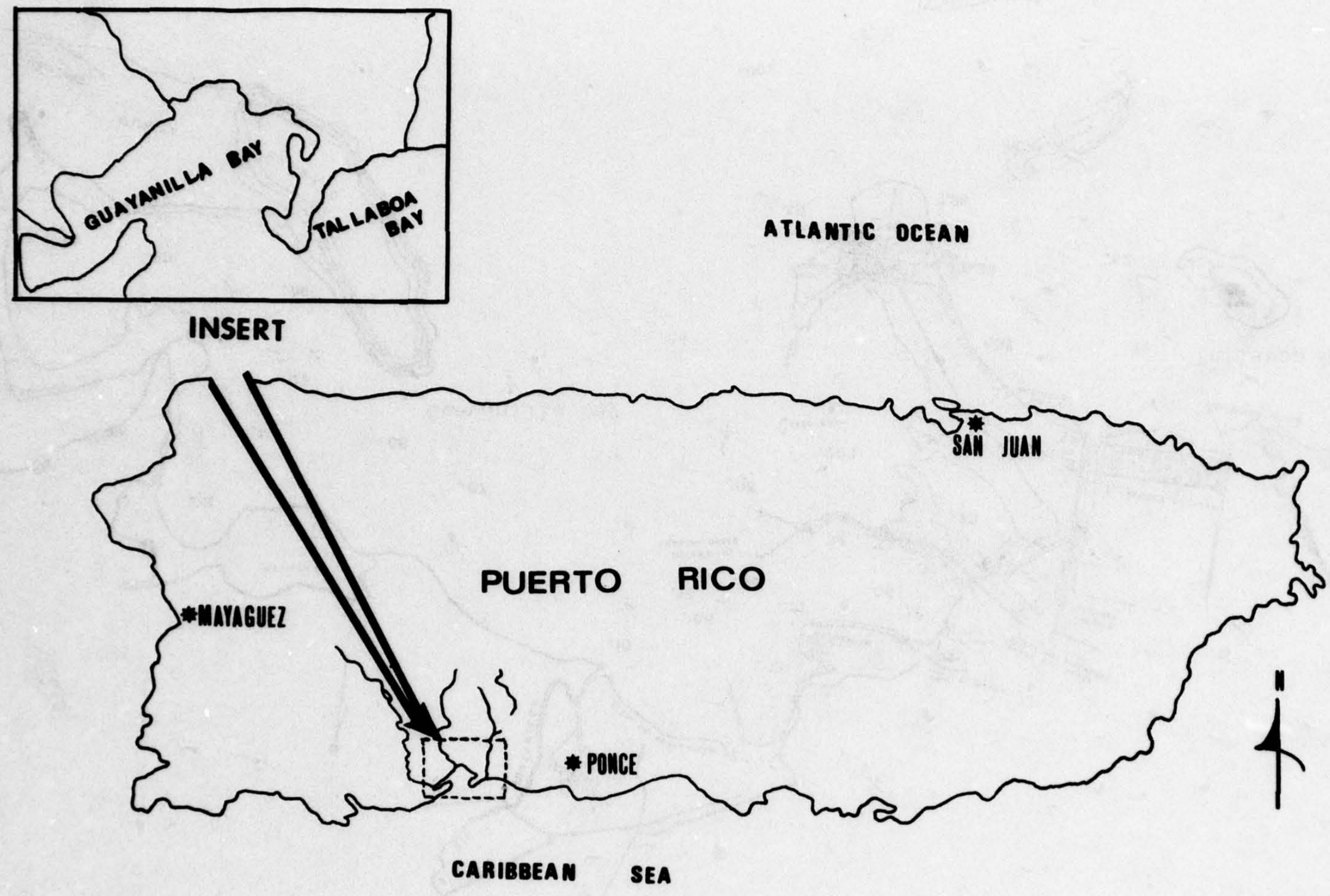

Figure 2. Location of study area in Puerto Rico.

FIGURE 3. Sediment petroleum hydrocarbon burden (g/100g, dry weight)

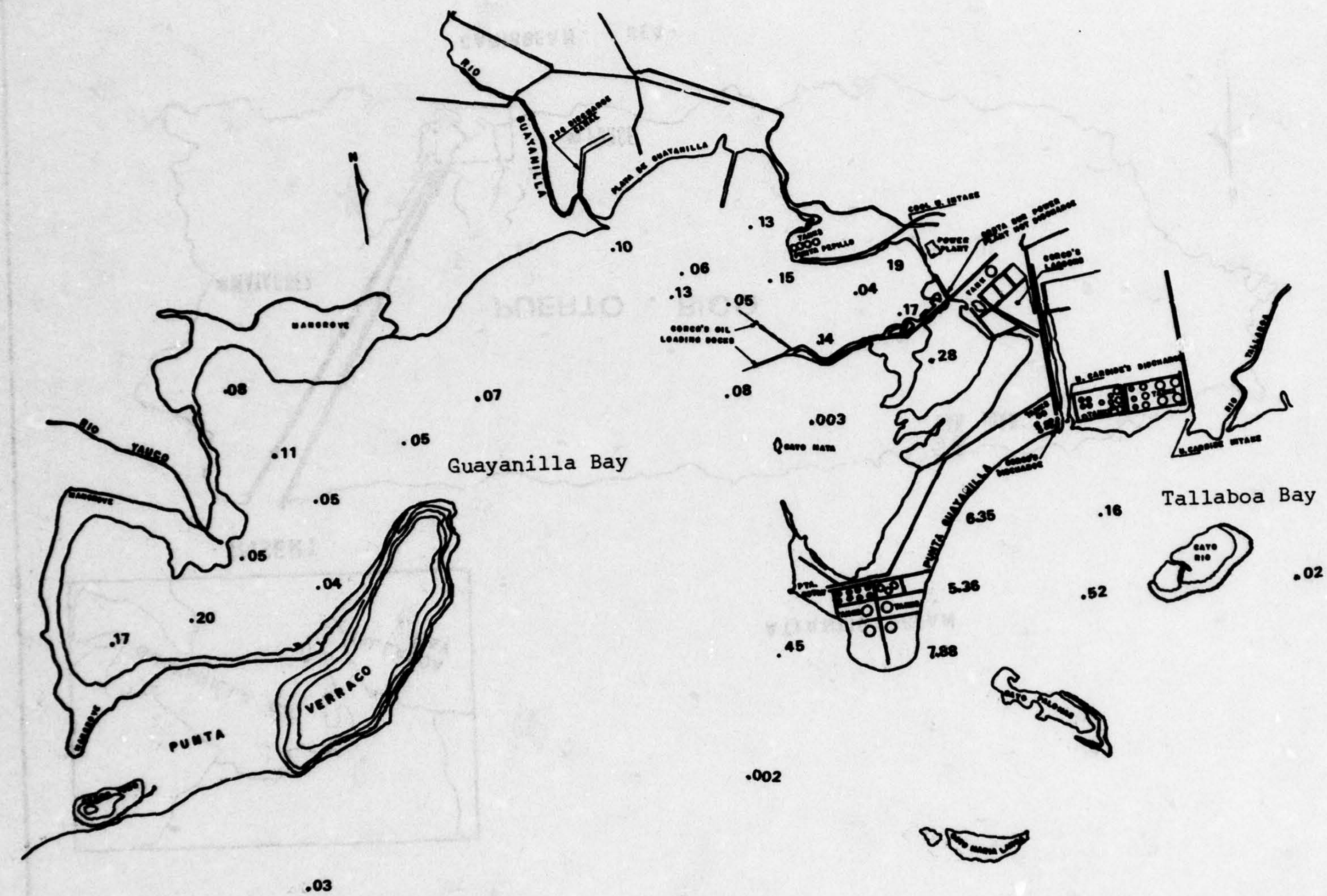

TABLE 1. MAJOR SPECIES IN THE TROPHIC STRUCTURE OF GUAYANILLA BAY, PUERTO RICO

PRIMARY PRODUCERS	
A. Mangrove	*Rhizophora mangle*
B. Macroalgae	*Acanthophora specifera* *Dictyota spp.* *Caulerpa spp.*
C. Benthic Diatoms	*Navicula spp.*
D. Filamentous microalgae	*Microcoleus sp.*
E. Phytoplankton	*Skeletonema costatum*
PRIMARY CONSUMERS	
A. Mangrove oyster	*Isognomen alatus* *Crassostrea rhizophora*
B. Jelly fish	*Phyllorhiza sp.*
C. Bivalve	*Tagelus divisus*
D. Hydroid	*Myrionema amboisnense*
E. Sponges	*Haliclona rubens* *Verongia sp.*
F. Tunicates	*Microcosmus exasperatus* *Polyclinum constellatun*
G. Snail	*Littorina angulifera*
H. Crabs	*Hexapanopeus caribbeaus* *Petrolisthes armatus*
I. Amphipods	*Elasmopus pocillimanus* *Caprellids spp.* *Melita apendiculata*
J. Shrimps	*Alpheus formosus*
K. Brittle stars	*Ophiotrix angulata*
L. Anemone	*Bartholemea annulata*
M. Polychaete annelids	*Branchiomma nigromaculata* *Sabellastarte magnifica*
N. Fishes: mullet sea bream	*Mugil curema* *Arcosargus rhomboidalis*

TABLE 1 (continued)

SECONDARY CONSUMERS	
A. Primary Carnivores:	
Striped mojarra	*Diapterus plumieri*
blue crab	*Callinectes sapidus*
yellowfin mojarra	*Gerres cinereus*
snake croaker	*Ophioscion adustus*
brown shrimp	*Penaeus brasiliensis*
B. Middle Carnivores:	
horse-eye jack	*Caranx latus*
cravalle jack	*Caranx hippos*
snook	*Centropomus undecimalis*
tarpon	*Megalops atlantica*
pelican	*Pelecanus occidentalis*
C. High Carnivores:	
shark	*Negaprion brevirotris*
barracuda	*Sphyraena barracuda*
man	*Homo sapiens*

(From Lopez and Teas, 1978)

WORKSHOP REPORTS - THE IMPACT OF OIL SPILLS

Leader - Chemical: FRED WEISS
Shell Development Company

Leader - Physical: RONALD L. KOLPACK
University of Southern California

Leader - Biological: DAVID FLEMER
U.S. Environmental Protection Agency

Leader - Socio-Economic-Legal: SIDNEY GALLER
U.S. Department of Commerce

REPORT OF THE WORKSHOP ON CHEMICAL IMPACT OF OIL SPILLS

Leader: Fred Weiss, Shell Development Company

With the sophisticated analytical equipment becoming available it is now possible to generate extensive data on the concentrations of inorganic and organic materials at any site. On the positive side, it is good to see how well these techniques have been used to generate data presented at this Conference. We are encouraged to see how effective is the use of glass capillary gas chromatography and gas chromatography combined with mass spectrometry for hydrocarbon component analysis, particularly for aromatic hydrocarbons. These techniques are powerful and are required but it must be realized that they are costly. As one speaker pointed out, it is necessary, in planning any study of ecological impact, to allocate a meaningful portion of the budget to chemical analysis.

The review group called again for attention to the need for intercalibration of methods on meaningful samples and the use of standard methods. Sampling techniques are critical in all our work. Members of the ASTM Committee on Water Analysis (D-19), a number of whom are in attendance at this Conference, have been active in these efforts in the United States. It is important to consider strengths and limitations of the available analytical methods which must be selected for different purposes. There is need not only for component analysis, but also simpler techniques have utility for surveying trends provided they are properly calibrated.

It is critical, as paper after paper confirmed, that strong coordination be established for all elements of an ecological study. At any sampling location, at any time, all samples for whatever use must be taken concurrently. In all matters, all disciplines must be interrelated.

Although laboratory studies and trajectory modelling calculations are important and necessary guides, our knowledge of the real world must always be in the field. A number of the field studies presented at this Conference have been excellent portrayals of our advances in conducting these essential studies. Field studies must be carried out over a period of time, as was well illustrated, and relate to the physical state of the area, the condition of the biota, and the composition of oil components present. Such studies should, where possible, provide more quantitative data on changes due to weathering factors particularly on hydrocarbon concentrations. It is necessary to examine water, sediments and animal tissues for specific hydrocarbon components. Such weathering factors as evaporation, solution, biodegradation and sediment impaction should be examined to attempt to derive more quantitative data than is presently available.

Data generated should be compared to background data wherever that is available as was described in several papers. In the past few years extensive data on area environmental characterization have been generated by U.S. agencies. These data should be published in a form readily available and utilizable by other investigators. In the future, when site specific environmental studies are made, the data should be collected in a uniform style for comparative purposes.

Laboratory studies designed to elucidate effects of oil on biota must use oils or hydrocarbons which correspond in all ways to the region of concern. Laboratory tests should be made at concentrations which are realistic and with mean-

ingful test materials such as water dispersed fractions or sediments. For basic laboratory biological studies, reference oils should be made available from definite sources such as the National Bureau of Standards. It is good that scientific investigations are underway on metabolism of petroleum components.

On the negative side, a caution should be emphasized to the chemist. That is, an ecological study must not turn into an exercise in analytical expertise. The significance of the sample analyzed in relation to the overall study must be paramount. We have not seen enough statistical analysis of the data obtained in some of these studies.

As we observe the progress in studies of the chemical impact of oil spills during the past decade we can see a strong positive trend in the improvement of the quality of the work. We did not want nor did we feel capable to order the quality of any of the papers but we do want to comment that the session yesterday evening on the AMOCO CADIZ was excellent and fit our desires for timely and critical review of an important concern.

The openness, the high level of expertise and the level of interest in the Conference generates high hope for continued good work.

REPORT OF THE WORKSHOP ON THE PHYSICAL IMPACT OF OIL SPILLS

Leader: Ronald L. Kolpack, University of Southern California

Four workshop sessions were conducted at the Keystone Conference to assess some of the problems and goals of oil spill investigations. Although the sessions were organized on the basis of disciplines, the plenary summaries for each of the workshops emphasized the desirability of cooperative efforts between disciplines in order to achieve the maximum benefit from all phases of the investigative efforts. The following discussion is an attempt to outline the range of topics related to the areas of physical oceanography, geology, and engineering which were considered during the two hour workshop session on physical impacts. Most of the attention during this discussion was focused on areas where more or better information is needed; however, several topics that appear to be adequately documented were also discussed.

Inasmuch as some of the major physical processes determine to a considerable extent the rates at which other processes subsequently affect the fate of spilled oil, it is important to establish a mass balance for different types of oil spilled under a variety of field conditions. Well documented measurements of the physical behavior of oil and the associated environmental conditions under which changes take place are primary requisites for developing mass balance relationships that can be used for predictive efforts and for guidance in clean-up operations. Comprehensive assessments of the fate of oil spills that are based on mass balance calculations will therefore provide the most reasonable approach for assessing the effects of oil spills. Although a considerable amount of information is available for these calculations, there is a need for more work on selected processes and for specific types of environments. For example, much additional information is needed regarding the behavior of spilled oil in marsh areas, beaches, and the intermediate of inner-shelf area between the surf zone and a water depth of approximately 25 meters. Sampling problems, the engineering aspects of oil spill clean-up, a variety of field and laboratory measurements of physical properties, and better coordination and planning of oil spill investigations are all high priority items for future work.

Participants in the physical workshop believed that additional work in determining how fast oil moves on a water surface with respect to wind is not necessary. In this case it appears that the available information is adequate with regard to the present ability to make field measurements, and any possible refinement will not justify the effort involved. Likewise, additional experiments involving experimental spills of small scale and some laboratory experiments should be critically evaluated before they are undertaken because the efforts may not lead to results which are applicable to large-scale spills. These comments are not intended to discourage all experiments of this type, but merely represent a concern for more attention to planning so that the expected goals are not unreasonable. Rate factors and precise relationships for some processes are difficult to obtain during field investigations of accidental spills. In these cases measurements from laboratory experiments or small experimental spills serve a useful purpose because the influence of some variables is easier to isolate and distinguish. On the other hand, complex interactions may take place in the natural environment and results obtained from simplified systems are often not directly applicable to many accidental spills.

Some aspects of the distribution and character of oil on the water surface are presently not well documented. A few topics in this area include the: small to intermediate scale distribution of oil on a water surface with respect to variations in oil composition and physical oceanographic parameters; mechanisms responsible for formation of mousse; relative effectiveness of dispersants on crude oil versus emulsified oil (mousse); time or stage in weathering or degradation of spilled oil when dispersants become ineffective; and relationship of oil/water interfacial tension variations to the spreading and distribution of oil on a water surface.

Marsh and beach areas exposed to oil from spills need a considerable amount of additional investigation. Items of concern include the effect of cutting vegetation, traffic from clean-up activities, and whether an area should be cleaned up or left alone. The flushing and leaching of oil in marshes or estuaries is a problem involving relatively long time periods, but these processes are important because they could provide a secondary source of contamination. Therefore, the conditions and rate factors involved should be investigated more extensively in order to devise methods of reducing potential chronic pollution and to enhance the recovery of an impacted area.

Many clean-up operations appear to be based on a repetitious learning experience at the local level. Although unique situations may require specific innovative techniques, there are many other general problems that are amenable to established methods. It seems that a systems approach for oil spill control efforts would yield a more balanced and effective method for integrating engineering, political, and environmental considerations in clean-up operations. This approach should be based on a synthesis of existing information so that priorities and recommendations could be established. Problems to be considered in this area include not only the factors involved in removing oil and debris from affected coastal areas but also the potential impact of disposal operations. The effects of oil transfer and disposal methods should be investigated in order to establish reliable and innocuous techniques for a variety of situations. Part of these investigations should involve follow-up studies to determine what happened around the area of previous disposal sites and if a secondary source of contamination was created by leakage from the repository.

The synthesis of background information for establishing recommended guidelines for supervisors of clean-up operations should include the identification of environmentally sensitive areas. Designation of particular seasons when various segments of the coastal areas are especially vulnerable would also assist in establishing alternative procedures to minimize the impact of these operations.

A problem facing many investigators is the location and procurement of information from previous oil spill investigations. At present this problem seems to be more acute in engineering than in some other disciplines. However, most investigators would benefit by having access to an efficient repository for published and unpublished reports as well as actual measurement values from oil spill investigations. No specific recommendations were put forth during the session other than the possibility that an existing facility might be able to assume responsiblity for this task. However, it seems that the requirements of this type of information center are somewhat different from those in existing facilities, especially in the area of a fast response capability, and a more specialized organizational framework would be more utilitarian.

A basic concern throughout the discussion was the need for greater coordination and planning of oil spill investigations. Future emphasis in this area should include not only the physical, chemical, biological and engineering aspects but also an integration of effort based on environmental habitats or environmental regions. For example, the approach, sampling design and analysis of data for a particular investigation would beneift by close working arrangements within groups investigating areas such as marshes, estuaries, beaches, the inner-shelf and offshore areas. The latter area might well be divided into water surface, water column and bottom segments of the environment. Aspects of the planning and coordination efforts of particular significance include sampling designs based on a similar time and geographic framework and consideration of interrelationships between traditional disciplinary components so that fate and effects relationships can be more precisely defined.

In the same vein as the preceding comments, there seems to be a very commanding need for a thorough synthesis or summary of the physical as well as the biological, chemical and engineering aspects of what is known about oil spills. A suggestion was advanced that perhaps a future conference would be based on a series of comprehensive reviews. Ideally there would be an adequate amount of discussion of the reviews so that the final manuscripts included pertinent contributions from the participants. This type of conference would entail a considerable amount of planning and effort, but such an achievement would most certainly reduce the redundancy that is evident in some studies of major oil spills which were i luenced by crises situations.

Although the time available for the workshop session was rather limited, the participants quickly focused their attention on topics that presently appear to be restricting a better understanding of the effects of oil spills. Consequently, it is hoped that the foregoing assessment will, to some extent, contribute to the advancement of knowledge in this area and will serve as a stimulus for additional effort in investigations of oil spills.

REPORT OF THE WORKSHOP ON THE BIOLOGICAL IMPACT OF OIL SPILLS

Leader: David A. Flemer, U.S. EPA

On Saturday morning, 17 June 1978, the session convened to discuss the meetings of the preceding days and to determine future directions and needs for coordinated ecological assessment.

The discussion was assisted by the formation of a five member panel whose[/1] members each made short introductory statements. The members were selected to represent a variety of interests including private consultants, federal agencies, academia, and state research laboratories.

As an overview, a list of priorities concerning spill situations was developed. The ranking suggests prevention as the most important avenue for environmental protection, followed by containment and cleanup, restoration, and finally, damage assessment. The rationale for the priorities was established on the basis that the research community could contribute more to environmental protection by focusing on studies that would minimize spills rather than solely the analysis of the effects of oil spills. The latter is important in terms of contributing to damage assessment which is required by the "super fund" legislation. It was pointed out that damage assessment provided an important informational feedback mechanism towards prevention by indicating those resources of highest priority for protection. Hence, activities contributing potentially to oil spills should receive most attention, especially in extremely sensitive environments.

The group expressed strong support for a strategy that would lead to a more organized approach for biological resource assessments. It was implicit that ecological values should be included with biological assessments. A direct benefit of such a strategy should be the enhanced cross communication between biologists, other scientists and decision-makers. As guidance for the development of a strategy, the group felt that the following questions had considerable merit:

1. <u>What are the impacts expected?</u>

An answer to this question would help researchers and other interested parties pre-plan and develop appropriate resources in the event of a spill. This question provides guidance to the planning of which parameters should be measured. Considerable information is available concerning the resources at risk from coastal zone management planning efforts.

2. <u>What degree of biological/ecological change is considered significant?</u>

This was acknowledged as a very difficult question that embraced value judgements as well as scientific implications. The group focused on the question of significance in terms of impact on resource use. It was accepted that responsible agencies can not respond to all biological/ecological changes and that a rationale containing criteria should be developed to assist in setting priorities for evaluating biological/ecological change. Time did not permit the group to examine this question in further detail.

3. <u>Can impacts be translated into economic terms?</u>

It was agreed that biology should play a major role in this area; however, one

very convincing argument was made that biologists should limit their activities to their profession and not bend to the pressure of taking on the "yolk" of the economist. The most satisfactory approach is one of a shared responsibility by biologists and economists.

4. What is the range of natural variation for the measured factors?

It was agreed that this question was important in making the allocation of effort for field sampling. Some factors of interest may have such high variation in time and/or space that they would consume a disproportional amount of money and manpower. In such cases some form of trend-analysis might be more appropriate than a highly quantitative statistical approach. Much of the effort of estimating natural variations could be performed for many areas prior to spill analysis.

5. What is the sampling effort required to document effects at a given level of statistical precision?

This question should encourage research planners to set priorities on sampling so that manpower and dollars would be most appropriately allocated. It was recognized that there are existing statistical procedures to assist in the allocation of sampling efforts relative to analytical and sampling variance.

6. What type of experimental controls are necessary to link causality?

This very important question was not discussed in depth; probably because everyone recognized its importance and felt that the appropriate controls are site specific. This topic warrants special consideration since causality should be very important in placing legal responsibility for payment of biological resource damage.

7. Finally, what level of dollars and manpower are required to implement a minimum sampling effort?

Implicit in this question is the need to identify what to measure as well as the degree of quantification required. The group did not explore this question in detail but agreement was reached that an answer would help sharpen objectives and make damage assessments more cost effective.

Following the above discussion, a number of additional points were made. The question was raised as to why examine subtle effects of an oil spill in the field as one often cannot interpret the significance of gross effects. It was pointed out that in some problem areas our knowledge is adequate to make useful interpretations of subtle effects whereas in other areas our knowledge is fragmentary and at best only gross effects can be interpreted.

The group discussed the problem of how to deal with publicity versus the real needs to study a particular oil spill. It appeared to the group that often large spills of oil in open coastal waters get more attention by the public, government agencies and researchers than small spills in enclosed areas where the ecological impact of the latter may be very high. The seven (7) questions outlined above were felt by the group to offer a useful approach when dealing with problems associated with excessive publicity.

An opinion was offered that the clean-up of oil spills is more of an organizational and management problem than one of development of new clean-up techniques.

There was general acceptance of this proposition by the group. Related to this question was the concern that clean-up activities often cause impacts and more research and development should focus in the area of minimizing such impacts. For example, machinery used to clean-up marshes following an oil spill can break down the root structure of marsh vegetation, thus resulting in a long-term loss of primary productivity.

One participant seriously challenged the use of the baseline concept in damage assessment of living resources. As usually applied in before and after studies, the baseline approach is associated with a high natural variation in the parameters of interest and it is difficult to draw firm conclusions regarding cause and effect relationships. It was also pointed out that the baseline approach of before and after studies involving environmental perturbations such as oil spills requires that a spill occur before the study design can be fully implemented. This is obviously a serious shortcoming.

More specific needs for ecological assessment were discussed. Foremost among them was the need for studies focusing on long-term/chronic effects. Among the methods suggested were quick substrate assessment, early organism sampling for long range pathology comparisons, and survey sheets for field volunteers to assure sampling integrity.

/1 Panelists include:
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REPORT OF THE WORKSHOP ON THE SOCIO-ECONOMIC-LEGAL IMPACTS OF OIL SPILLS

Leader: Sidney R. Galler, U.S. Department of Commerce

Rapporteur: Peter Fricke, East Carolina University

The socio-economic and legal aspects of oil spills were considered by a panel, chaired by Dr. Sidney Galler, which included Edwin Dubiel, of the Attorney General's Office of the State of California, Herbert Kumpf, of NOAA Southeast Fisheries Center, and myself. Since this was the first meeting of this nature on these topics, it was felt that a panel discussion, followed by a review of issues by all of those present would enable us to develop a notion of common concerns and problem areas.

We were asked to look at the prevention issues related to oil spills and their impact assessment, or perhaps more accurately, the processes by which national priorities for the protection of the marine environment could be ranked within a general theme of impact assessment. The discussion proved to be very lively indeed, and if Dr. Bates had not reminded us of this final session, we would probably still be debating the issues.

Of these topics, perhaps the most contentious was the argument put forward by Dr. Dubiel that the dollar cost of pollution is the only criteria by which pollution damages can be assessed. He argued that legal criteria of damage to the public good require that the biological and ecological damage be assessed in terms of finite values. Since the only agreed finite value in our society is a monetary one, the State of California has developed a "price" list for marine organisms damaged by pollution. Thus, a polluter is held liable to pay $1.00 for every fuzzy flatworm (Thysanozoon sp.) killed, and $0.30 for each barnacle. (Copies of this "price" list are available from Dr. Dubiel.)

Dr. Kumpf and I were more concerned with the problems of impact assessment studies. A major point that we felt needed to be addressed was the lack of interdisciplinary data crossover. It was noted that frequently social scientists are working without adequate descriptions of the types of data bases that biologists, chemists, and oceanographers are using when they undertake their work.

A second point that we raised concerned the lack of effective coordination among pollution control agencies. While in the field of damage assessment, efforts of coordination of research and agency involvement had developed following the *Argo Merchant* spill, too often the preventative aspect of coordination was missing. The complexity of regulations being put forward by the agencies frequently are at cross purposes. For example, when a permit to dredge is issued and all the environmental impact statements have been cleared, does it make sense to use a dredging operation involving a crane which leaks oil and gasoline, but complies with standards for equipment used in the construction industry?

As a corollary to the need for agency coordination, there was seen to be a need for some form of information clearing house. There are many who are involved in research in the field of damage assessment at the moment, but there appears to be little cross-fertilization of projects and the results tend to be overlooked.

So far as research needs are concerned, a primary objective must be to develop some form of unit value for marine resources. The California method, as explained by Dr. Dubiel, places a cash value on different organisms - a value which is obtained by asking a marine specimen supplier how much he would charge for that species -but this does not take into account the social or the economic costs associated with the diminution of that species. There is a need to take this unit of value and use it in developing economic models so that account can be taken of factors such as change in use, fashions in taste, and temporal change. In this way one can begin to assign values for resources such as a pretty beach, or a coral reef. The legislation discussed by Couper and Fidell in their papers will require us to assign values to, for example, the ability of citizens to go swimming in the ocean. This will in turn require the ability to use standard evaluation criteria, which eventually will satisfy the legal requirements for a uniform code of practice.

Dr. Kumpf and I felt that there should be an expansion of the public's education about oil spills and their impacts. Currently, a concerned layman picks up a newspaper and sees doomsday headlines about an accident without being able to relate that incident to any others or to understand the real nature of any damage or benefits that may occur. For example, little is known by the layman, or anyone else, about the level of cost at which pollution is prohibitive. If such a level could be determined, it would assist planners and the layman in understanding the transportation costs, the operation costs of refining the oil, and eventually the cost of the goods to the consumer. This understanding would in turn permit the public to make a choice between relatively cheap petroleum products and some pollution from transportation, or expensive products and no pollution.

Dr. Kumpf was also concerned that those laws and regulations which currently exist be enforced, and their impact measured before any new regulations for the control of pollution be enacted. The legal requirement for pollution control and cleanup is a very complex one at present. In addition to State and Federal laws, there are administrative rule-making procedures. There are also international regulations, to which the United States is party, concerning pollution of the high seas. If any real benefit is to be obtained from these rules, Dr. Kumpf felt, and we all agreed, they should be put into practice and their effect considered before being replaced.

As a social scientist who has taken part in pollution damage assessment studies, I am particularly concerned about the adequacy of fishery data, both biological and socio-economic, for use in models which can be utilized in the determination of impacts. For example, a port which has a mixed fleet of deepsea and inshore fishing vessels will suffer very different impacts from one which has a fleet of inshore vessels.

A further information need is for data on employment related to the use of the marine resources. Daniel Palm and Elizabeth Wilman discussed, in their papers presented at this Conference, the problems of identifying employment related to the recreational use of the resource. An important factor in damage assessment in terms of employment is that of set-offs. If the pollution caused a cost of X, what could be the benefits, say Y, of that pollution? Palm has suggested that the benefits could be very real, since in his study cleanup crews earned higher wages than they would have in the normal economy of the region.

Finally, there is a realm of costs for which data is almost completely lacking. These are the psychic costs suffered by persons affected by pollution. In the study

of the Argo Merchant oil spill carried out for NOAA at East Carolina University, we found that many of our randomly selected sample of the population of Cape Cod and the Islands believed that they had been affected by the oil spill. The effects they referred to were feelings of distress, of anger and bitterness towards government agencies, oil companies and the shipping industry. I would suggest that a manifestation of these psychic costs is the legislation currently before Congress.

The discussion of all these points was very lively. Initially there was an impression, largely dispelled by Dr. Dubiel, on the part of those associated with the oil industry that in many cases they were being unfairly penalized for decisions they had made which they thought were in the public good. The uncertainty caused by shifts and changes in public opinion or environmental affairs was said to have increased during the past two decades, and in consequence, petro-chemical business decisions were increasingly difficult to make. There were others in our discussion group who favored the view that any form of impact by hydrocarbons in the marine environment was something that should be avoided, and therefore, industrial interests should be made to justify their activities.

The discussion, however, did bring a general agreement that the assessment of all costs and benefits related to pollution had to be brought to light in impact studies and in planning for the prevention of spills. These costs and benefits were seen to include those of employment, transportation, and fisheries to local communities and regions. The workshop participants felt that further discussion of socio-economic-legal factors was necessary and we felt that a conference on this topic in the near future would be most appropriate.

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